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Pollutants from Synthetic Fuels Production Environmental Evaluation of Coal Gasification Screening Tests

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Research Triangle Park, NC

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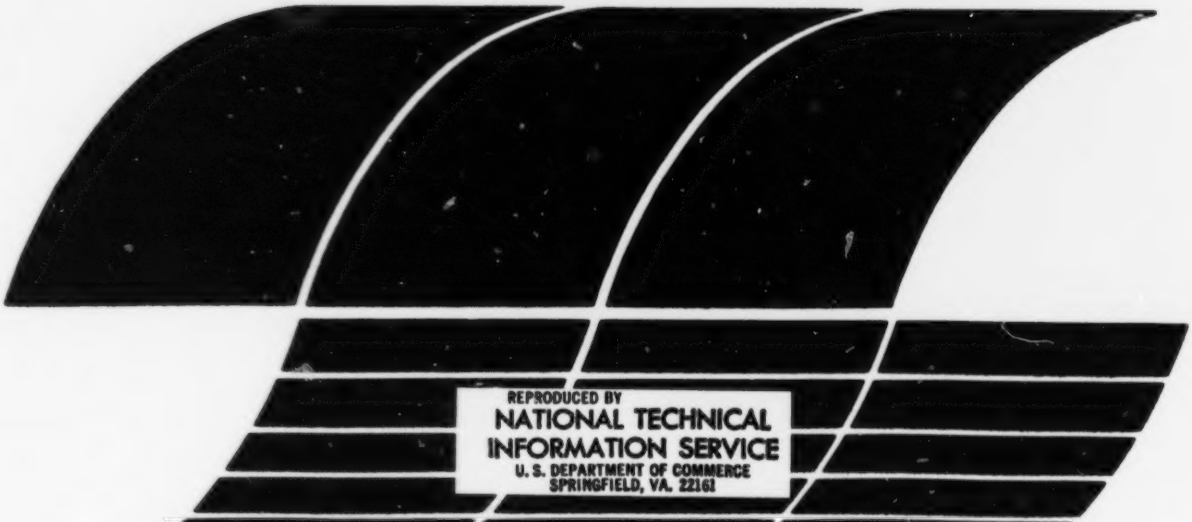
Interagency Energy/Environment R&D Program Report



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16. ABSTRACT
The report gives results of an environmental evaluation of 38 screening test runs using a laboratory-scale, fixed-bed coal gasifier to study pollutants generated during the gasification of various coals. Pollutants were identified and quantitative analyses performed for tars, aqueous condensates, volatile organics, primary gases, and reactor residues. Tar partition fractions were also generated and studied for each coal providing distributions of insolubles, organic acids and bases, polar and nonpolar neutrals, and polynuclear aromatic hydrocarbons. Showing the greatest potential for adverse health effects are: oxygen-containing species and PNAs in the tars and aqueous condensates; carbon monoxide, benzene, and hydrogen sulfide in the primary gas streams; and certain trace elements in the reactor residues. Bioassays of various coal gasification effluents showed the crude tars and selected tar fractions to have a potentially mutagenic character.

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Tars	Synthetic Fuels	07C
Condensates		07D
Organic Compounds		
Gases		
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Pollutants from Synthetic Fuels Production: Environmental Evaluation of Coal Gasification Screening Tests

by

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ii

POLLUTANTS FROM SYNTHETIC FUELS PRODUCTION: ENVIRONMENTAL EVALUATION OF COAL GASIFICATION SCREENING TESTS

ABSTRACT

A series of screening test runs have been performed using a laboratory-scale, fixed-bed coal gasifier in order to study the potential pollutants generated during the gasification of various coals. Potential pollutants have been identified and quantitative analyses performed for tars, aqueous condensates, volatile organics, primary gases and reactor residues. Tar partition fractions have also been generated and studied for each coal providing distributions of insolubles, organic acids, organic bases, polar neutrals, nonpolar neutrals, and polynuclear aromatic hydrocarbons. Species showing the greatest potential for adverse health effects are: phenolic species and polynuclear hydrocarbons in the tars and aqueous condensates; carbon monoxide, benzene, and hydrogen sulfide in the primary gas streams; and trace elements in the reactor residues, including arsenic, lead, and mercury. Bioassay tests on various coal gasification effluents also have been performed. The crude tars showed significant potential for inducing mutagenic changes in living cells. The organic tar bases, polynuclear aromatics, and polar neutrals were found to be responsible for this behavior. Overall, this study indicates that the potential environmental problems of coal conversion, while reasonably complex, can be resolved through a systematic approach involving chemical testing and process control.

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1.0 INTRODUCTION

A research project directed to the study of the environmental aspects of the production of synthetic fuels from fossil energy resources is being conducted at the Research Triangle Institute in Research Triangle Park, North Carolina. A report on the facility construction and preliminary tests was prepared.[1] That report describes the design and construction of the gasification facility including the reactor and associated coal feed system, the sampling and analysis system development, as well as the related data collection and chemical analysis capability. This report has been prepared as a companion to reports previously issued on (1) coal gasification screening test results and (2) the sampling and analysis methodology which has been developed for use in the project.[2,3]

Some 38 gasification tests have been conducted to provide screening test results relevant to potential pollutants generated from the gasification of the alternative types of coal available for use in the United States. The initial work was directed toward establishing the range of operating conditions over which the laboratory reactor could be successfully operated as well as the development of analytical chemical methods for the sampling and analysis of the streams which exit the gasifier. More importantly, this project has been directed toward the gasification of a range of coal types and the extensive chemical analysis of the product gas, aqueous condensate, gasifier tar, and reactor residue. The fossil fuel sources which have been utilized include Illinois No.6 coal, Western Kentucky No.9 coal, Pittsburgh No.8 coal, Montana Rosebud coal, Wyoming subbituminous (Smith-Roland) coal, and North Dakota Beulah-Zap lignite.

Generally, the gasifier operating conditions have been chosen to approximate those of large scale gasifier operations producing low heating value fuel gas or synthesis gas. However, coal has been fed to the laboratory gasifier via a pressurized lockhopper in such a manner that the complete charge of the hopper has been passed to the reactor in a single cycle. Thus, the coal feed has been a batch process while the addition of air and steam to the gasifier has involved continuous flow throughout a gasification test run. Hence, operation of the gasification reactor during the screening tests is referred to as being in the semibatch fixed-bed mode. (A continuous coal feeder has been added to the laboratory gasifier for subsequent gasification test runs.)

The effluent concentrations from semibatch runs are averaged by integration over the time of the run so as to simulate the steady-state concentrations of a continuous process. In this manner, the semibatch reactor produces effluent concentrations which appear to provide a reasonably good simulation of gas product compositions from full scale process gasifiers. The composition of the oils and tar resulting from the RTI laboratory gasifier has been found to compare quite closely to similar material produced in larger scale units in regard to both quantity and composition where comparable data are available.

Future reports on the work of this project will be directed toward the generation and control of potential pollutants in coal gasification under various operating conditions. Studies using the laboratory gasifier have involved variation in various quantities so as to determine the influence of coal type, coal particle size, reactant flow rates, chemical additives, and other factors. The information being generated in this project is intended to provide a basis for the assessment of the potential health and the environmental significance of the effluents from coal gasification processes. The project results should also lead to suggested process modifications and/or control technology developments which can achieve substantial reductions in potential emissions.

The environmental assessment of processes for the generation of clean fuels from coal was initiated earlier this decade as described by Magee, Hall, and Varga.[4] That work provided focus to the currently existing data base on the nature of the existing technology for the production of synthetic fuels from fossil fuel resources and the chemical nature of the various process streams to the extent that such was known at that time. The need for an environmental assessment methodology was given impetus by the increased importance of energy independence for the country. The basis for this methodology has been the "multimedia environmental goals" (MEGs) which represent an attempt to quantitate the objectives to be achieved in controlling emissions as well as ambient concentrations of chemical constituents from process operations. MEGs quantities have been provided in an extensive compilation.[5,6] More than 600 master list entries of chemical species have been arranged into categories. A total of 85 categories (26 organic and 50 inorganic species) have resulted. Each compound or species is assigned a "discharge multimedia environmental goal" and an "ambient multimedia environmental goal" for each of the primary environmental media, viz., air, water, and land. The discharge multimedia environmental goals (DMEGs) which are used in this study generally carry two subscripts, be they explicit or implicit. The first defines whether the value refers to air (A), water (W), or land (L); the second, whether the value refers to human health (H) or the ecological environment (E). In this study, the health-based DMEG values were used primarily. The ecology-based DMEG values were used only to generate a comparative ranking of pollutants. No ambient multimedia environmental goal values were used in this study.

Discharge severity is a measure or index of degree to which the concentration of a particular substance is at a potentially hazardous level in a discharge (effluent). Discharge severity values which are dimensionless are computed as the quotient of the stream discharge concentration and the DMEG value. Discharge severity values must be distinguished as to the physical phase to which they refer as well as to whether the value is computed for health or for ecological effects.

The environmental assessment methodology being developed by EPA also includes a systematic approach for the biological testing of samples.[7] Bioassay procedures are designed to complement the chemical and physical procedures which are also in use as a part of an integrated environmental assessment program. In this study the Ames mutagenicity test and the Chinese hamster ovary cell mutagenicity and cytotoxicity assays were used based on the various considerations of cost, time requirements, reliability, and degree of public acceptance. These and other available short-term tests for carcinogens, mutagens, and other genotoxic agents have been described in recent reports.[8,9] The preliminary results from the bioassays conducted as a part of this project have been recently presented.[10]

Generally, it must be emphasized that neither the use of a laboratory reactor nor the chemical/biological testing program of this study guarantees that results therefrom will necessarily be duplicated in full scale gasification systems involving equipment designed and personnel trained for commercial operation. Yet, an attempt was made to generate results having some (high) degree of scalability to commercial gasification plant size within the constraints of time and funds available.

The more general impacts of large-scale synthetic fuel plants are now receiving attention in the country, particularly in the coal producing states. Potential impacts from coal mining, transport, processing, conversion, and end-product use include significant social and economic aspects in addition to the environmental and occupational health aspects. Methodological techniques to analyze socio-economic impacts are now available,[11] and, the continuing progress being made in the development of an integrated, multimedia environmental assessment approach for synthetic fuels processes is reported in the "Environmental Review of Synthetic Fuels," a quarterly publication of the EPA Industrial Environmental Research Laboratory, Research Triangle Park, NC 27711.

2.0 SCREENING TEST EXPERIMENTS

The semibatch gasification test runs which have been conducted in the RTI laboratory gasifier have been numbered 1 through 58. Runs 1 through 6 are referred to as preliminary tests, Runs 8 through 45 are referred to as screening tests, and Runs 46 through 58 are designated parametric test runs. These designations have been applied to distinguish among the objectives at play during the time period when these runs were performed. Generally however, all the Runs 1 through 58 represent screening tests in the sense that alternative coal types were being studied (screened) under various operating conditions. The parametric test sequence involved a more systematic approach in that the feed rates of air, steam, and other additives were carefully controlled so as to examine the specific influence of these operating conditions (parameters). It is the intent of this report to present primarily results for the Runs 7 through 45, particularly those runs for which a judgment has been made that meaningful data resulted therefrom. The fossil fuel feed material utilized in Runs 7 through 58 have been described in previous reports of this project.[2]

2.1 COALS GASIFIED

The coals which have been utilized primarily in this project have been Illinois No.6, Western Kentucky No.9, and Pittsburgh No.8 bituminous coals; Montana Rosebud and Wyoming Smith-Roland subbituminous coals; as well as North Dakot Beulah-Zap lignite. (A few runs were also made with other materials including Western Kentucky No.11 coal char, Pennsylvania Red-Bottom anthracite, and North Carolina humus peat.) These coals ranged in heating value from 12,300 to 7,900 Btu/lb for the Pittsburgh No.8 and North Dakota lignite, respectively. (The North Carolina humus peat possessed a heating value of 5,000 Btu/lb.)

Other important characteristics of the primary coals used in this study were volatile matter content, fixed carbon, sulfur content, and free swelling index. The volatile matter content of the Western Kentucky No.9 and the

Wyoming subbituminous coals were essentially the same at 38 percent, the Illinois No.6 and Montana Rosebud coals were at 32 percent, and the Pittsburgh No.9 coal was 29 percent. This latter coal possessed the highest fixed carbon content at 57 percent; the Illinois No.6 was 47 percent; the Montana Rosebud and Wyoming subbituminous were approximately 38 percent each with the North Dakota lignite being 35 percent. The Western Kentucky No.9 coal possessed a total sulfur of 4.8 percent of which 2.9 percent was organic sulfur and 1.8 percent pyritic sulfur. The remaining sufur was as sulfate, which was essentially negligible for the coals studied in this project. The sulfur content of the Illinois No.6 coal was 3 percent which was distributed as 1.2 percent organic and 1.7 percent pyritic. The Pittsburgh No.8 coal possessed a sulfur content of 2.5 percent of which 1.3 was organic sulfur and 1.2 pyritic sulfur. Further, the total sulfur content of the Montana Rosebud, Wyoming subbituminous, and North Dakota lignite were the same at 0.6 percent. However, these three coals varied in their sulfur distribution, the organic sulfur being 0.2, 0.1, and 0.5 percent, respectively for these coals.

The free swelling index was also measured for the coals used in this project. The Pittsburgh No.8 coal possessed a free swelling index of 7, which was so high that successful conversion of this coal to a high level of carbon conversion was not feasible in the fixed-bed laboratory reactor. The Western Kentucky coal possessed a free swelling index of 4 while the Illinois No.6 coal possessed a value of 3. The free swelling index for the other coals utilized were negligibly low.

2.2 REACTOR AND SIGNAL PROCESSOR

The reactor was constructed from a nominal 3-inch diameter (7.5 cm), schedule 160, type 310 stainless steel pipe and is approximately 1.2 m in length. Above it is located the coal hopper and coal feed system. This consists of a nominal 2-inch (5 cm) diameter, schedule 40 steel pipe, which is approximately 0.5 m in length. The sight glass joints are connected to the coal feed system with flanges at each end. The sight glass permits the operator to view the descent of solid feed as it is added to the reactor. A pneumatically actuated Jamesbury stainless steel ball valve is located between the feed hopper and the reactor. Once the coal solids have been admitted into the reactor space, a bed of solids exists within the reactor which is supported by a flow distributor (see Figure 1).

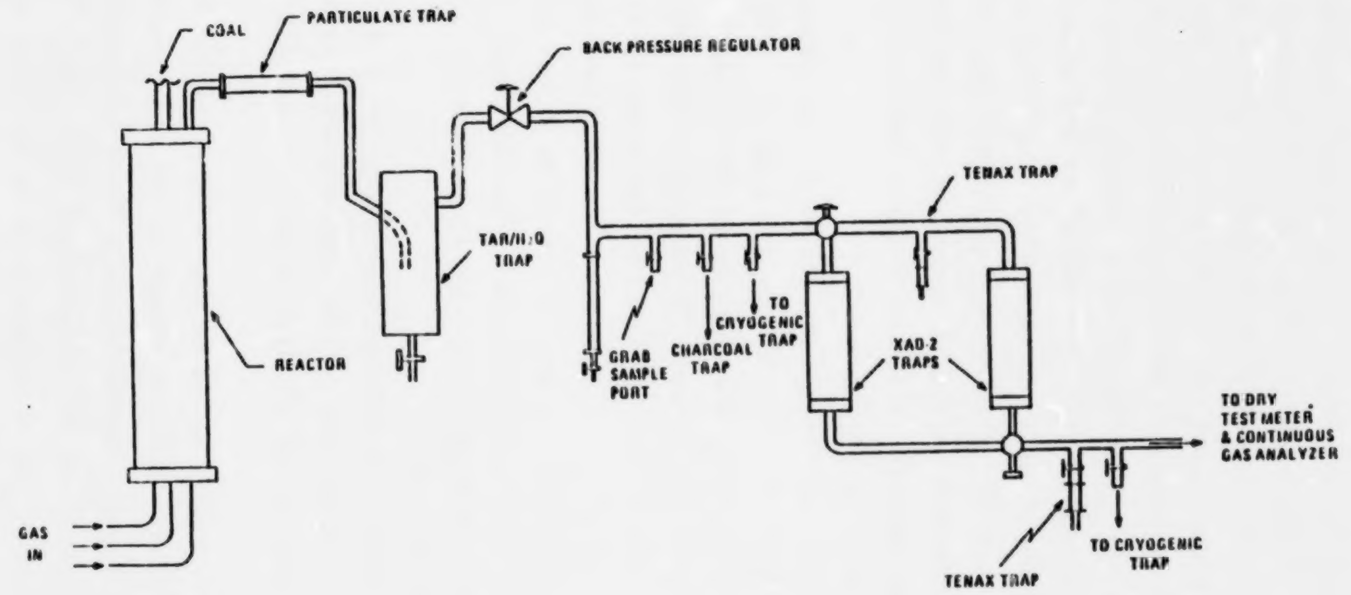
COAL
PARTICULATE TRAP
BACK PRESSURE REGULATOR
TAR/H_2O TRAP
REACTOR
GAS IN
TENAX TRAP
GRAB SAMPLE PORT
CHARCOAL TRAP
TO CRYOGENIC TRAP
XAD-2 TRAPS
TO DRY TEST METER & CONTINUOUS GAS ANALYZER
TENAX TRAP
TO CRYOGENIC TRAP

Figure 1. Gasifier and sampling train.

Steam and other gases are introduced into the bottom of the gasification reactor below the distributor plate. The reactor operating conditions and other data are presented in the Table 1. The steam is generated in a series of three furnaces. The steam supply tubing has been insulated to prevent heat losses. Strip heaters are also utilized in order to ensure that superheated steam is fed to the reactor under closely controlled conditions.

The gas stream then passes to the tar trap where a volume of approximately 8 liters is available for the accumulation of tar and aqueous condensate. This trap may be tapped periodically for removal of the accumulated material. This trap is water-cooled in order to remove the latent heat of condensation from the accumulated material. The product gases then pass from the tar trap and through the high-pressure enclosure, expand to near ambient pressure through a backpressure regulator and enter a glass sampling system for collection and analysis of major effluents.

A number of pressure and temperature values are continuously monitored, periodically recorded and available for digital display. Pressure transducers are used to continuously monitor the pressure of the nitrogen or air, the steam feed and the product gas stream. Thermocouples are located at the outlet of each of the three steam furnaces, at the steam inlet to the reactor and in the bottom and top of the coal hopper. In addition, the reactor furnace contains thermocouple detectors in each of its three zones. The reactor thermowell contains six distinct thermocouple locations over the length of the reactor. Further, thermocouples are located at the product gas outlet and within the tar-condensate trap.

The three steam generating furnaces are controlled by a single Lindberg control system. Over long periods of time, temperatures may be controlled at steady-state levels representing the desired saturation and/or superheat steam condition.

The vertical furnace that surrounds most of the reactor during operation is controlled in essentially the same manner as the three steam generating furnaces. This furnace does, however, contain three independently operated heated zones, each of which can demand a maximum of 2.6 kW. The furnace controller allows the selection of temperatures in the range of 200°C to 1200°C for each zone. The three-zone electric furnace controller contains a datatrack programmer which will permit the introduction of any preselected temperature sequence for the three zones.

TABLE 1. OPERATING CONDITIONS FOR SELECTED SCREENING TESTS

	Run 6 Illinois No.6 Bituminous	Run 44 Illinois No.6 Bituminous	Run 16 Illinois No.6 Bituminous	Run 20 Illinois No.6 Bituminous	Run 21 Illinois No.6 Bituminous	Run 23 Illinois No.6 Bituminous
Steam (g)	5796	1084	3704	3672	4713	1952
Air (g)	350	4753	1350	1368	1720	3288
Coal (g)	1034	1250	1569	1578	1543	1594
Air/Coal			.86		1.1	2.1
Steam/Coal	5.6	.87	2.4	2.3	3.1	1.2
Air/Steam	.060	4.38	.35	.37	.35	1.8
T_{max}* °C	820	976	941	1006	984	1020
Carbon Conversion (%)	67.1	87.7	89	84.5	97	96
Sulfur Conversion (%)	93.6	91.9	93	86.0	98	95
Tar Yield (g/g Coal)	.0154	.0210	.036	.0342	.033	.033

*Time-averaged maximum bed temperature

Table 1 (continued).

	Run 25 Montana Rosebud	Run 26 Montana Rosebud McKay Subbituminous	Run 31 Pittsburgh No. 8 Residue	Run 32 Wyoming Smith/Roland Subbituminous	Run 33 Wyoming Subbituminous	Run 35 Wyoming Subbituminous
Steam (g)	748	1332	892	500	500	527
Air (g)	2482	346**	1249	2073	2097	2461
Coal (g)	1491	1488	443	1360	1396	1420
Air/Coal	1.7				1.5	1.7
Steam/Coal	.50	1.3	2.0	.37	.36	.37
Air Steam	3.4	.18**	2.8	4.1	4.2	4.6
T_{max}* °C	1006	1010	975	975	1010	790
Carbon Conversion (%)	99.7	99.9	66.4	99.5	98.9	97
Sulfur Conversion (%)	85	98.7	64.8	92.5	91	85
Tar Yield (g/g Coal)	.018	.0192	NA	.0110	0.012	.029

*Time-averaged maximum bed temperature
**Oxygen

Table 1 (continued).

	Run 36 North Dakota Lignite	Run 38G Illinois No.6 Bituminous	Run 41 Western Kentucky Bituminous	Run 43 North Dakota Lignite	Run 45 Wyoming Smith/Roland Subbituminous	Run 47 Wyoming Smith/Roland Subbituminous	Run 51 North Dakota Lignite
Steam (g)	639	404	1390	422	600	528	447
Air (g)	1939	1499	3060	2022	2290	2275	1430
Coal (g)	1444	NA	1250	1458	1427	1430	1491
Air/Coal	1.3		2.5	1.4			
Steam/Coal	.44	.54	1.1	.29	.42	.37	.30
Air/Steam	3.1	3.71	2.2	4.8	3.8	4.3	3.2
T_{max}* °C	916	963	1034	914	932	946	939
Carbon Conversion (%)	99.7	NA	99.8	99.4	96.5	98.1	99.99
Sulfur Conversion (%)	91	NA	98	80	92.6	94.3	74
Tar Yield (g/g Coal)	.013	NA	.030	.0072	NA	.0208	.0119

*Time-averaged maximum bed temperature.

Pressure, temperature, and flow rate signals from the reactor control system are provided to the signal processor for collection, reduction, analysis, storage and reporting. The data acquisition system includes a signal processor (DEC PDP-11/34) with 64K words of memory, dual disk drive, an alpha-numeric CRT and a 30 cps DECwriter. (This signal processor and its accessories have been programmed for data processing in support of the gas chromatographic units which are used to analyze gaseous effluent samples.)

The CRT terminal and the hard copy printer (DECwriter) have a full keyboard, which permits dialog between the system and its users. These terminals are used for entry of operator's commands, display of process conditions and the generation of messages and data lists.

2.3 SAMPLING AND ANALYSIS

Details of the sampling techniques and chemical analysis procedures which have been developed and used in this project are discussed in detail in a separate report.[3] However, a brief description of these subjects is appropriate here.

The effluent gas stream from the fixed-bed reactor passes through a particulate trap which is insulated to maintain hot gas conditions. This is immediately followed by a refrigerated condenser unit which removes aqueous condensate and low volatile organic material at the system pressure. The condenser unit is followed by a backpressure regulator.

A glass sampling system has been installed on the low pressure side of the backpressure regulator. This system includes ports for grab samples and a valving system for direct adsorbent cartridges. A port also exists for removal of a continuous gas stream for infra-red analysis. Further, the primary gas stream passes through a continuous dry gas meter to measure the total volumetric flow of the effluent stream.

Raw gas samples were collected periodically during the gasification test. These samples were contained in special glass sample bulbs and maintained under controlled conditions in a specially designed sample storage chest. These samples are analyzed for primary (permanent) gases, sulfur-containing gases, and volatile benzene-related species.

A Carle AGC-111-H automated gas chromatograph is used for the analysis of the major product gases (H_2, CO, CO_2, CH_4, and N_2). In addition, it has the capability of monitoring ethane, ethylene, hydrogen sulfide, oxygen and water.

The system utilizes three columns for analysis which includes a molecular sieve-13X, a porapak N and a reference OV-101 column. The complete analysis of all gases mentioned above can be accomplished every 15 minutes using a series-bypass-backflush arrangement.

A continuous gas analysis system (Horiba) is also used throughout gasifier runs. This system is housed in a portable cabinet and is used for measurement of H_2, CO_2, CO, CH_4 and O_2 continuously. A sample conditioner removes traces of condensibles from the gases via refrigeration (1°C) prior to their entering the continuous analyzers. CH_4, CO, and CO_2 are measured using nondispersive infrared detectors, H_2 using a thermal conductivity analyzer and O_2 using a paramagnetic analyzer.

The tar samples are complex. Solvent fractionation is performed before direct analysis is undertaken. This approach is described in a companion report.[3] Solvent partition schemes have been devised, most notably by researchers from the tobacco industry, in which group separations are accomplished on the basis of similar chemical properties, e.g., acids, bases, etc. The latter approach is more practical, particularly if fractions are to be chromatographed further. A detailed schematic of the partitioning procedure used is shown in Figure 2 and is a modification of a method developed for air particulate extracts. Partitioning results are summarized in Table 2.

Five fractions are produced by application of the scheme: acids, bases and three neutral fractions. These three fractions are designated nonpolar (aliphatics and 1-2 ring aromatics), medium-polar (polynuclear aromatic hydrocarbons-PNAs) and polar (oxygenated material). Each group is then either analyzed directly by gas chromatography/mass spectrometry (GC/MS), or is chromatographed using high performance liquid chromatographic (HPLC) techniques.

Glass capillary gas chromatography has also been applied for quantitation of PNA materials in tar. A chemically bonded temperature stable (300°C) methyl-silicone capillary column was used. The 'GROB' splitless method of sample injection is used and approximately 5-15 μg are injected for detection of the heavier PNAs, e.g., benzo(g,h,i) perylene. The splitless technique consists of injecting 2 to 3 μl of the sample and then 30 seconds later, opening the splitter to remove the excess solvent. This prevents a long solvent tail as illustrated in the accompanying chromatogram (Figure 3) in which 21 PNAs have been identified based on retention times of standards. At

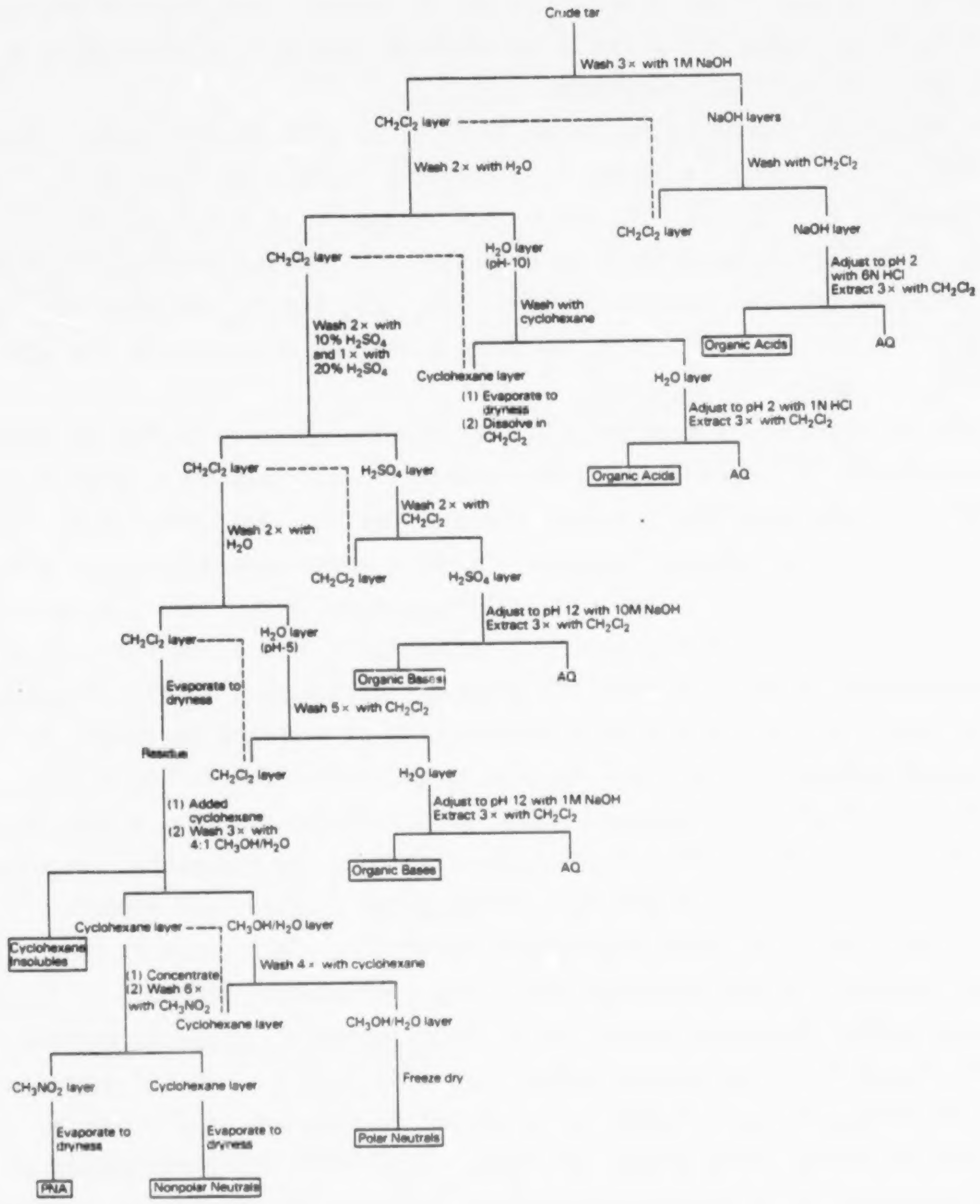
Crude tar
Wash 3× with 1M NaOH
CH_2Cl_2 layer
NaOH layers
Wash 2× with H_2O
Wash with CH_2Cl_2
CH_2Cl_2 layer
NaOH layer
CH_2Cl_2 layer
H_2O layer (pH-10)
Adjust to pH 2 with 6N HCl Extract 3× with CH_2Cl_2
Wash with cyclohexane
Wash 2× with 10% H_2SO_4 and 1× with 20% H_2SO_4
Organic Acids
AQ
Cyclohexane layer
(1) Evaporate to dryness
(2) Dissolve in CH_2Cl_2
H_2O layer
Adjust to pH 2 with 1N HCl Extract 3× with CH_2Cl_2
CH_2Cl_2 layer
H_2SO_4 layer
Organic Acids
AQ
Wash 2× with CH_2Cl_2
Wash 2× with H_2O
CH_2Cl_2 layer
H_2SO_4 layer
Adjust to pH 12 with 10M NaOH Extract 3× with CH_2Cl_2
CH_2Cl_2 layer
H_2O layer (pH-5)
Organic Bases
AQ
Evaporate to dryness
Wash 5× with CH_2Cl_2
Residue
CH_2Cl_2 layer
H_2O layer
(1) Added cyclohexane
(2) Wash 3× with 4:1 CH_3OH/H_2O
Adjust to pH 12 with 1M NaOH Extract 3× with CH_2Cl_2
Organic Bases
AQ
Cyclohexane layer
CH_3OH/H_2O layer
Cyclohexane Insolubles
(1) Concentrate
(2) Wash 6× with CH_3NO_2
Wash 4× with cyclohexane
Cyclohexane layer
CH_3OH/H_2O layer
CH_3NO_2 layer
Cyclohexane layer
Freeze dry
Evaporate to dryness
Evaporate to dryness
Polar Neutrals
PNA
Nonpolar Neutrals

Figure 2. Partition scheme for crude tars.

Table 2. TAR AND PARTITION RESULTS FOR SELECTED SCREENING TEST RUNS (g produced/g coal loaded)

Run No.	16	21	23	41	25	33	35	36	43
Coal Type*	I	I	I	WK	M	W	W	Z	Z
Tar Acid	0.0048	0.0033	0.0042	0.0016	0.0018	0.0032	0.0086	0.0016	0.0018
Tar Base	0.0022	0.0025	0.0023	0.0021	0.0008	0.0004	0.0010	0.0004	0.0004
Polar Neutral	0.0029	0.0017	0.0013	0.0016	0.0008	0.0009	0.0027	0.0005	0.0007
Nonpolar Neutral	0.0107	0.0046	0.0036	0.0038	0.0012	0.0025	0.0053	0.0012	0.0015
PNA	0.0120	0.0176	0.0174	0.0186	0.0112	0.0048	0.0103	0.0043	0.0024
Insolubles	0.0035	0.0035	0.0037	0.0024	0.0005	0.0002	0.0012	0.0002	0.0004
Total Tar	0.0361	0.0331	0.0325	0.0301	0.0163	0.0120	0.0291	0.0082	0.0072

*Coal Type: I = Illinois No.6, WK = Western Kentucky No.9, M = Montana Rosebud, W = Wyoming (Smith-Roland) subbiutminous, and Z = North Dakota (Zap) lignite.

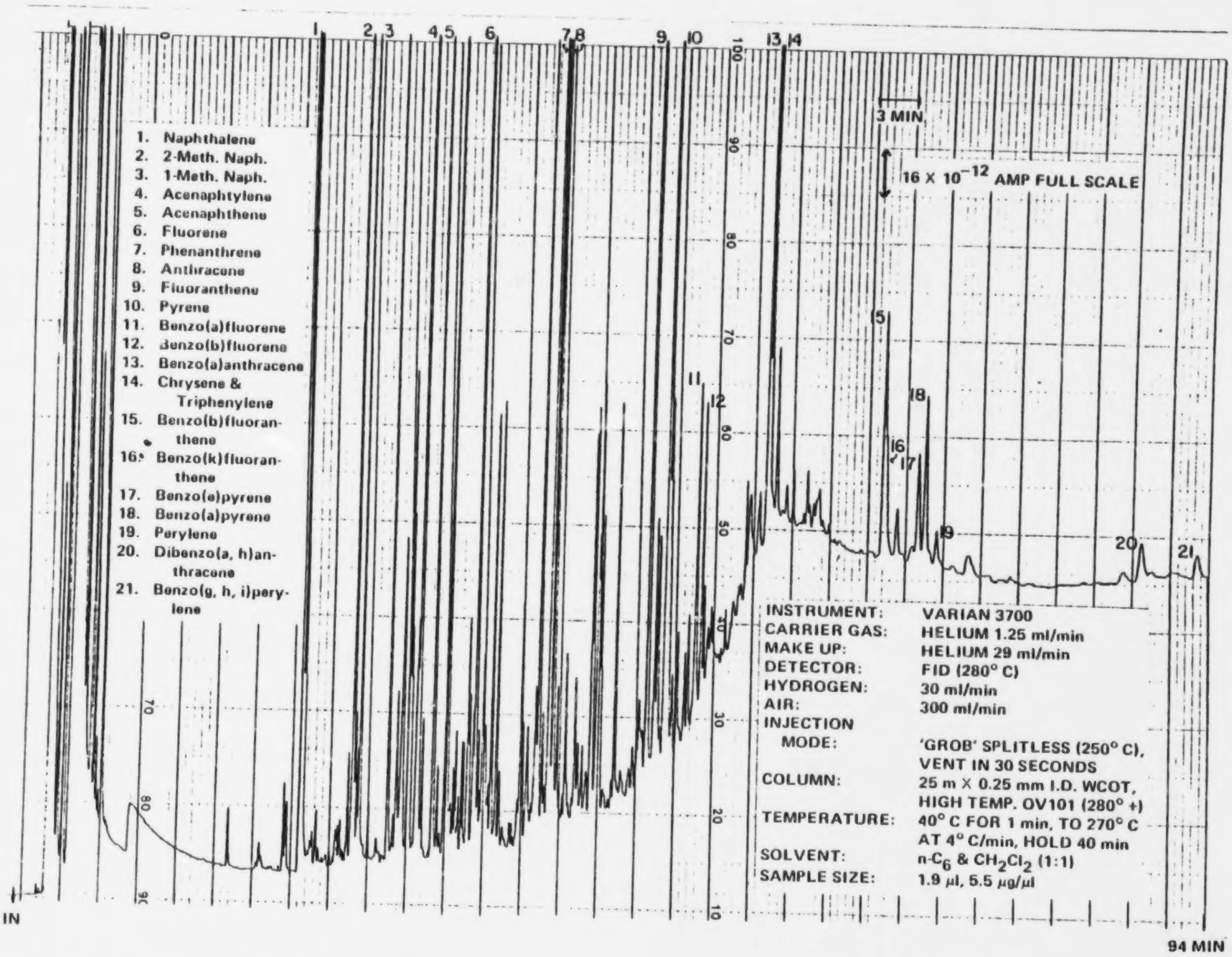

Figure 3. PNA fraction of coal gasifier tar by capillary GC-FID.

present, it is planned to use this temperature stable column in a GC/MS for confirmation of these compounds. In the future, the capillary-GC-FID technique will be routinely applied to PNA analyses of coal conversion tars and condensates.

2.4 BIOASSAY SAMPLES

Selected coal samples were introduced into a rotating jar mill for 16 hours to pulverize the samples. The coal dust so generated was sieve-classified and retained for bioassay. Further, crude tars and related samples from selected gasification tests in the RTI laboratory gasifier were tested in whole (neat) form and as partitioned (see Figure 2).

The samples which have been subjected to bioassay in this project include raw coal dusts from North Dakota lignite, Wyoming subbituminous coal, Western Kentucky No.9 coal, and Illinois No.6 coal. These samples were prepared to -200 mesh (-74 microns) using sieve screens. The bioassays used on the dusts were the Ames mutagenicity screening test and the Chinese hamster ovary (CHO) cell assays which employ growth kinetics and clonal efficiency. These latter tests primarily measure the toxicity of mammalian cells, i.e., CHO cells, to the samples under study.

The Ames and CHO assays were also employed to study effluents from the RTI laboratory gasifier. These effluents included crude tar and selected tar partitions from North Dakota lignite, Wyoming subbituminous coal (3 runs), Western Kentucky No.9 coal, and Illinois No.6 coal. In addition, the aqueous condensate and XAD-2 adsorbents were assayed for the run which used Western Kentucky No.9 coal.

3.0 ENVIRONMENTAL ASSESSMENT APPROACH

So as to achieve comprehensive environmental assessments for synthetic fuel production processes, the Industrial Environmental Research Laboratory at Research Triangle Park (IERL/RTP) has underway a program to develop procedures for environmental assessment. These involve sampling and quantitative chemical analyses of the various streams which discharge from synthetic fuel processes. The methodology prescribes a systematic approach for interpreting data obtained in the sampling and analysis campaigns. The use of multimedia environmental goals (MEGs) provides the capability to quantify measures for the potential severity of the process streams under study. Thus, the characterization of waste streams involves not only a determination of their flow rate and chemical constituents but a determination of the potential degree of severity to be associated with each species and/or the entire stream. Further, a source assessment methodology (SAMs) is under development in order to weight the severity measures based on the mass flow rates of the streams in question.

3.1 LABORATORY GASIFICATION

The Research Triangle Institute is conducting a project to establish the range of operating conditions over which a laboratory reactor can be successfully operated for the generation of environmentally significant samples. This reactor has been utilized to generate samples from a range of U.S. coals. These samples have been characterized via chemical and bioassay tests, the data being subjected to MEG methodology so as to evaluate the degree of severity of the individual chemical species contained in the various effluents of the laboratory gasifier. This project is being conducted in support of the overall environmental assessment program. More generally this program includes the development of an environmental assessment data base for alternative coal conversion processes.[12-14] Additional specific results have been reported by Bombaugh.[15] More detailed studies have also been conducted.[16] These studies have been performed in relation to fixed-bed coal gasifiers, which represent the gasification reactor type which has been developed to commercial scale. Additional studies are underway throughout the country to develop other gasification reactor types. Environmental considerations must also be applied in an overall environmental assessment program to these alternative types. Slagging fixed-bed gasification has been under study at the Grand Forks Energy Technology Center of the U.S. Department of Energy.[17] Fluidized-bed gasification has been under study at various locations throughout the United States, including the Synthane process of the Pittsburgh Energy Technology Center[18] and the Hygas process of the Institute of Gas Technology.[19] (Additional interest exists among various organizations in the development of entrained bed gasifiers.) While the results of this study cannot be directly applied to either commercial fixed-bed or other gasifier types, it does provide information as to the compounds and magnitudes which can occur in process effluents be they fugitive emissions or discharges.

In the RTI laboratory gasifier screening tests, steam-to-carbon ratios have been investigated over the range from 0.4 to 18 g/g and air-to-carbon ratios from 0 to about 4 g/g. Although the air-to-coal ratio has varied depending upon the intended method of supplying heat to the reactor, the steam-to-coal ratio has been predominantly in the range of 0.5 to 3.0 g/g. (Excessive steam simply passes through the reactor and results in additional aqueous condensate formation in the reactor condenser system). Maximum bed temperatures have been in the range of 900 to 1000°C. Carbon conversions have ranged from 52 to near 100 percent, oxygen-to-coal ratios from 0.0 to 0.9 g/g, and steam-to-oxygen ratios from 0.9 to infinite. Both internal and external heat has been supplied to the reactor system. (See also Table 1.)

3.2 SAMPLING AND ANALYSIS

The environmental assessment methodology which has been utilized encompasses both the Level 1 and Level 2 techniques for sampling and analysis. These techniques have been described in various papers presented at the symposia dealing with environmental aspects of fuel conversion technology.[20] As has been the case for the sampling and analysis activities relating to the laboratory gasification project, the Level 2 approach has been utilized for organic species while the Level 1 approach has been taken in most cases for inorganic species. This means that specific compounds have been quantitated where such is possible for organic species using gas chromatography or mass spectrometer/gas chromatography techniques. For most inorganic species only an elemental analysis has been feasible. Trace element analyses were achieved both by atomic absorption spectrometry (AAS) and neutron activation analysis (NAA). The Table 3 presents the major elemental composition of the gasifier tars.

TABLE 3. PRIMARY ELEMENTS OF GASIFIER TARS

Weight Percent of Element in Tar

Run No.	Coal Type	% C	% H	% N	% S	% O
6	Illinois #6	78.7	6.3	1.3	2.9	10.9
15	Illinois #6	87.5	6.1	1.3	1.9	3.2
16	Illinois #6	87.6	6.2	2.1	1.6	2.4
21	Illinois #6	87.7	6.1	1.4	1.8	3.1
23	Illinois #6	86.0	5.8	1.6	2.5	3.8
25	Montana (Rosebud)	88.6	6.0	0.8	0.7	4.0
33	Wyoming Sub-bit.	86.5	6.0	0.8	2.4	4.3
35	Wyoming Sub-bit.	83.0	7.7	1.5	0.5	7.4
36	North Dakota Lignite	86.1	7.0	1.3	0.7	4.9
41	West. Kentucky #9	86.3	6.1	1.6	2.7	2.8
43	North Dakota Lignite	82.3	7.5	1.8	0.9	7.0
METC	Montana (Rosebud)	78.0	6.6	1.1	2.4	11.0
METC	West. Kentucky #9	80.0	8.7	1.9	2.7	(6.7)
METC	New Mexico Sub-bit.	84.4	7.2	1.7	1.4	(5.3)

3.3 MEG METHODOLOGY

The multimedia environmental goals (MEGs) methodology provides a method to classify potential pollutants in a comprehensive manner. The discharge multimedia environmental goal (DMEG) value provides a measure of the toxicity or hazard potential of individual compounds or chemical species based on existing data. This approach does, of course, encompass a "conservative" feature. Compounds which possess no known threshold value for exhibiting toxic mutagenic, carcinogenic or other health effects can be assigned MEG values which are derived from those other compounds in the same chemical category. MEG values so determined are referred to as supplemental MEG values. No such MEG values have been used in this report, however. In addition to the MEG compilations referred to earlier,[5,6] additional reports have been issued which increase the data base considerably.[21,22]

A comparison of DMEG (health) and DMEG (ecology) values is presented in Table 4. Here it is seen that except for phenolic species and mercury the health-based values are equal to or exceed the magnitudes of the ecology-based values. Although both health-based and ecology-based values are used in this study, the results are typically quite similar as to the potential severity of the various compound categories which have been identified and studied herein.

3.4 BIOASSAY TESTS

The Level 1 environmental assessment approach for screening environmentally significant samples includes a series of short-term bioassays for the detection of acute biological effects.[7] This includes both health-related and ecological test. The health tests are provided to screen for both acute toxic and potential chronic (i.e., carcinogenic) health effects. The health tests include the Ames *Salmonella typhimurium* reverse mutation assay. This test employs the Salmonella bacteria to screen complex process samples for their mutagenic potential. Since mutagenicity is a forerunner to carcinogenicity, then this technique can provide an initial screening of samples to determine whether the sample may contain carcinogenic agents. Further, the Chinese hamster ovary (CHO) cells provide a convenient medium in which to assay liquid and perhaps solid samples. The additional assays included in the Level 1 biological series were not employed in this study. These include the rabbit alveolar macrophage (RAM), aquatic ecological tests, and other suggested procedures.

Table 4. COMPARISON OF HEALTH AND ECOLOGY BASED DMEG* VALUES FOR AQUEOUS PHASE POLLUTANTS

	Name	DMEG(health) µg/ℓ	DMEG(ecology) µg/ℓ	DMEG(health) / DMEG(ecology)
1.	benzene	4.5E4	1.0E3	4.5E1
2.	naphthalene	7.5E5	1.0E2	7.5E3
3.	phenanthrene	2.5E4	NA	NA
4.	benzo(a)pyrene	3.0E-1	NA	NA
5.	phenol	5.0	5.0E2	1.0E-2
6.	cresol	5.0	5.0E2	1.0E-2
7.	2,4 xylenol	5.0	5.0E2	1.0E-2
8.	ammonia	2.5E3	5.0E1	5.0E1
9.	aminotoluene	1.65E3	4.0	4.1E2
10.	benzidine	1.5E4	1.0E2	1.5E2
11.	hydrogen sulfide (or $S^=$)	NA	NA	NA
12.	benzenethiol	7.5E3	NA	NA
13.	sulfate ($SO_4^=$)	NA	NA	NA
14.	thiocyanate (SCN^-)	NA	NA	NA
15.	cyanide (CN^-)	5.0E2	2.5E1	2.0E1
16.	chloride (Cl^-)	1.3E6	NA	NA
17.	arsenic (As)	2.5E2	5.0E1	5.0E0
18.	cadmium (Cd)	5.0E1	1.0E0	5.0E1
19.	chromium (Cr)	2.5E2	2.5E2	1.0E0
20.	copper (Cu)	5.0E2	5.0E1	1.0E2
21.	iron (Fe)	1.5E3	2.5E2	6.0E0
22.	lead (Pb)	2.5E2	5.0E1	5.0E0
23.	mercury (Hg)	1.0E1	2.5E2	4.0E-2
24.	manganese (Mn)	2.5E2	1.0E2	2.5E0
25.	selenium (Se)	2.5E2	5.0E1	5.0E0

* Discharge Multimedia Environmental Goals (DMEG) values.

The assay of choice for initial biotesting of the coal gasification fractions is the Ames *Salmonella* assay based on reverse mutation of histidine-requiring mutants of *Salmonella typhimurium* to wild type upon addition of a mutagen. Spot or plate-incorporation tests are commonly used, with activation requirements for promutagens supplied by addition of an Aroclor 1254-induced mammalian rat liver S-9 microsomal preparation. The accuracy of this system, cost, time requirements (2 days), and reliability for a wide variety of compounds has led to its acceptance for mutagenesis screening.

Coal dust samples and crude tars from coal gasification were tested along with selected samples of raw condensate water and XAD-2 adsorbent. The tars were fractionated using a partitioning scheme (Figure 2) into six fractions; acids, bases, polar and nonpolar neutrals, polynuclear aromatic hydrocarbons (PNA) and cyclohexane insolubles.

Salmonella typhimurium strains TA 98, (used to detect frameshift mutations) and TA 100 (used to detect base substitution mutations) were obtained directly from Dr. Bruce N. Ames (Biochemistry Department, University of California, Berkeley). NADPH (tetrasodium salt, Type 1) and known positive mutagens (highest purity available) were obtained from Sigma Chemical Company. Dimethylsulfoxide (spectrophotometric grade) and sucrose were obtained from the Fisher Chemical Company. Agar was obtained from Difco Laboratories.

The procedures for handling the strains and preparing media components were those of Ames, et al.,[26] with the following exceptions: (a) Craig-Dawley male rat livers were used as the source for metabolic activation (S-9); NADPH was added directly to the plate (per plate, 0.10 ml containing 320 mg NADPH); (c) use of a 2.5 ml agar overlay rather than a 2.0 ml overlay; (d) S-9 microsomal preparation was diluted in 0.25M sucrose at a concentration of 3 mg protein/ml and added at protein concentrations of 3.0 mg/plate for initial testing; and (e) bacterial strains are centrifuged and concentrated in normal saline at 10^{10} cell/ml. After nontoxic doses were identified, additional testing was performed with S-9 concentrations of 0.8, 1.5, 3.0 and 6.0 mg/plate. The S-9 microsomal preparation was obtained from rats injected with Aroclor 1254.

The standard is divided into four parts as follows:

Toxicity Testing, Plate Incorporation Method

Some 200-300 cells per dish were plated in a histidine-positive overlay. Tests were done with and without induced S-9. When plates did not contain S-9, deionized water replaced NADPH solution and 0.25 M sucrose solution replaced the S-9 microsomal preparation. Test compound was added at 0.1 ml/plate in all tests. The viability ratio was calculated as the ratio of surviving colonies, with sample, to colonies without sample. A value less than one indicates toxicity of the sample compound; a value of one or greater indicates no toxicity.

Mutagenesis Testing, Plate Incorporation Method

With S-9--To a tube containing 2.5 ml of histidine-negative overlay agar was added 0.1 ml of S-9 microsomal preparation, 0.1 ml of NADPH (prepared by dissolving 3.2 mg of Sigma NADPH in 1.0 ml of cold sterile deionized water), 0.1 ml of a solution of test material or positive control compound in dimethylsulfoxide, and 0.1 ml of bacterial suspension [washed once and concentrated 10-fold in isotonic saline solution (8.5 g salt per liter)] to give $\sim 10^9$ cells per plate.

Without S-9--Prepared as above, 0.1 ml of 0.25 M sucrose solution replaces the S-9 microsomal preparation and 0.1 ml of deionized water substituted for the NADPH solution.

The mutagenic ratio was calculated as the ratio of revertants/plate, with sample, to spontaneous revertants per plate. (A mutagenic ratio of 3 or more when the viability is greater than 0.5 is considered a positive response.)

Positive Mutagen Control Testing, Plate Incorporation Method

Using histidine-negative overlay, $\sim 10^9$ cells were plated in each dish. Known mutagens were tested to assure that the strains are active and the S-9 preparation was activating promutagens to the desired levels. If known positive controls did not show proper mutagenic activity, the test components (cultures and/or S-9) are rejected. Control compounds used included sodium azide, quinacrine HCl, 2-nitrofluorene, and 2-anthramine.

Sterility Testing, Plate Incorporation Method

Sterility tests were conducted with histidine-positive overlay plates, using the amounts of components employed in the tests. Components tested were sample(s), positive controls, solvent(s), water, 0.25M sucrose solution, saline, microsomal preparation (S-9), and NADPH solution.

Mammalian Cell Cytotoxicity Assays

Mammalian cells grown in tissue culture serve as a substitute for the whole animal as a screening tool for assessing the cellular toxicity of xenobiotics to mammals. In this assay, a stable tissue-culture cell line with well known growth characteristics and biochemistry serves as the test system. The putative toxins challenge the cells by addition to the growth medium when the cells are growing as a monolayer, attached to a plastic substrate (plastic culture dish).

The cell type chosen for this study is the Chinese hamster ovary (CHO) cell line introduced in 1967 as a parent diploid cell for the production of mutant cells. The cell line is available from the American Type Culture Association, and although no longer diploid, possesses a constant chromosome number (ploidy), is fairly resistant to infections, is relatively easy to maintain in culture on defined medium, and divides rather rapidly (12-14 hr doubling-time) for a mammalian cell. The CHO cells grow in a uniform population and the levels of various key metabolites involved in their metabolism can readily be measured. The CHO cell exhibits consistent growth kinetics when cultured under standard conditions and when provided with a standard nutrient culture medium.

Inhibition of cell growth was determined in this study by two assay methods. In the growth kinetics assay, cells were explanted onto a growth substrate by seeding 10^5 cells into a 35 mm diameter plastic culture dish, allowing 24 hr for cell attachment, and incubating with the compound to be studied for 24 hr. The medium was then replaced with fresh medium, and the dishes incubated for one one week, with cell counts of control and treated cultures performed at 24 hr intervals. A control growth curve, exhibiting the lag, logarithmic, and stationary phases of growth was also generated.

The second method quantitated the ability of a single CHO cell to give rise to a viable colony (or clone) of cells. This cloning efficiency assay was performed by seeding a small number of cells (200-1000) in a 60 mm culture dish, allowing 24 hr for attachment, adding test substance, incubating for 24 hr, replacing medium, and incubating about 10 days, or until studies provided an overall screening assay to quantitate general cytotoxicty. The parameters measured are the ability of cells to grow and divided as members of a large population, and the ability of a single cell to survive the toxic insult, and given rise to progeny.

Tissue culture was obtained from KC Biologicals (Lanexa, Kansas) and from Grand Island Biologicals (NY). Cells were obtained from the American Type Culture Association. Disposable tissue culture dishes, flasks and pipettes were obtained from Corning Corporation. All water used in preparing medium was tripled distilled after passing through ion-reducing resins.

4.0 MEG METHODOLOGY RESULTS

The multimedia environmental goal values which have previously been discussed have been utilized to evaluate results of the various gasification tests conducted in the RTI laboratory gasifier.

4.1 INTRODUCTION

Four distinct effluent streams emerge from the laboratory gasification facility. These are the product gas streams which have passed through a condensate trap, the aqueous condensate, the tar (tars and oils), and the reactor residue (ash). The composition of these streams have been determined as previously described in this report. The concentrations of each stream has been averaged over the duration of the gasification test runs so as to express the individual components on a mass/unit volume basis in the case of gaseous and liquid samples and component of unit mass sampled stream in the case of tar and ash effluents. The concentration in each stream is then divided by the appropriate DMEG value to achieve results in the form of discharge severities. Since for many compounds both DMEG health and DMEG ecology values were available, it was possible to compute a discharge severity health and a discharge severity ecology for each of these species. The experimentally determined concentrations are tabulated in the Appendix to this report and the discharge severity values expressed by stream type are presented in Tables 5 through 21.

4.2 HEALTH-BASED RESULTS

Based on the results of the multimedia environmental goals assessment, it was found that a variety of compounds and compound types occur at concentrations which exceed the goal as expressed in DMEG form. However, the number of compounds occurring at quite high values of discharge severity was found to be relatively small. In the gas phase, carbon monoxide was determined to possess the highest discharge severity (health) value. This was true without regard to coal type. Next were compounds possessing a DS (health) order of

TABLE 5. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #6, Illinois #6

Run #6 Gas Stream
Flow Rate = 6.7E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	10,000	1,000
2	53B	Hydrogen sulfide	1,000	1,000
3	99A	Hydrogen	100	
4	53C	Carbonyl sulfide	10	
5	42B	Carbon dioxide	10	
6	13A	Methanethiol	10	
7	25A	Thiophene	10	
8	13A	C_2H_6S	10	
9	01A	Methane	10	10
10	18A	C_2-Phenols	10	
11	18A	Cresols	10	
12	15A	Benzene	1	10
13	01B	Propylene		10
14	53D	Carbon disulfide	1	
15	53B	Sulfur dioxide	1	
16	25A	Methylthiophene	1	
17	15B	Indene	1	
18	25A	Dimethylthiophene	1	
19	15B	Methylindene	1	
20	18A	Phenol	1	
21	21A	Naphthalene	1	
22	01A	Ethane	1	
23	15A	Toluene		1

Run #6 Condensate Stream
Flow Rate = 2.4E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
		none		

TABLE 5. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #6 Tar Stream
Flow Rate = 9.5E-04 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	49A	Arsenic	1,000	10
2	53A	Sulfur	100	
3	46A	Lead	1	

Run #6 Ash Stream
Flow Rate = 2.2E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	54A	Selenium	10	1

TABLE 6. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #16, Illinois #6

Run #16 Gas Stream
Flow Rate = 1.3E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	1,000	1,000
2	15A	Benzene	100	1,000
3	15A	Toluene	10	1,000
4	53B	Hydrogen sulfide	1,000	100
5	25A	Thiophene	100	
6	99A	Hydrogen	100	
7	42B	Carbon dioxide	10	
8	53C	Carbonyl sulfide	10	
9	01A	Methane	10	
10	13A	Methanethiol	10	
11	53D	Carbon disulfide	10	
12	15B	Indene	1	
13	15B	Methylindene	1	
14	15B	Dimethylbiphenyl	1	
15	15B	C_3-Benzenes	1	
16	01B	Propylene		1

Run #16 Condensate Stream
Flow Rate = 9.4E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Cresols	100,000	1,000
2	68A	Chromium	1,000	10
3	18A	Phenol	10	100
4	49A	Arsenic	10	1
5	82A	Cadmium	10	10
6	46A	Lead	10	

TABLE 6. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #16 Tar Stream
Flow Rate = 3.1E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	21C	Benzo(a)pyrene	1,000,000	
2	21B	Triphenylene	1,000,000	
3	21C	Dibenzo(a,h)anthracene	100,000	
4	18A	Cresols	100,000	1,000
5	10C	Naphthalene	10	100,000
6	10C	Benzidine	100	10,000
7	21B	Benz(a)anthracene	1,000	
8	21A	Acenaphthylene	100	
9	21D	Benzo(g,h,i)perylene	100	
10	21A	Phenanthrene	100	
11	15A	Biphenyl	100	
12	21A	Acenaphthene	100	100
13	53A	Sulfur	100	
14	22C	Benzo(b)fluoranthene	100	
15	18A	Phenol	10	100
16	25B	Benzothiophene	10	
17	21A	Anthracene	10	
18	21C	Benzo(e)pyrene	10	
19	22B	Fluoranthene	1	
20	22D	Indeno(1,2,3-CD)pyrene	1	
21	22C	Benzo(k)fluoranthene	1	
22	22B	Benzo(a)fluorene	1	
23	23C	Carbazole	1	
24	21A	1-methylnaphthalene	1	
25	22B	Benzo(b)fluorene	1	

Run #16 Ash Stream
Flow Rate = 1.8E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	49A	Arsenic	10	1
2	54A	Selenium	1	

TABLE 7. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #20, Illinois #6

Run #20 Gas Stream
Flow Rate = 1.3E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	10,000	1,000
2	01B	Ethylene		10,000
3	53B	Hydrogen sulfide	1,000	100
4	99A	Hydrogen	100	
5	42B	Carbon dioxide	10	
6	53C	Carbonyl sulfide	10	
7	01A	Methane	10	1

Run #20 Condensate Stream
Flow Rate = 7.1E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
		none		

TABLE 7. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #20 Tar Stream
Flow Rate = 3.2E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	21C	Perylene	10,000,000	
2	21A	Naphthalene	10	100,000
3	49A	Arsenic	1,000	100
4	21A	Phenanthrene	1,000	
5	23B	Acridine	1	1,000
6	21B	Chrysene	100	
7	21A	9-Methylanthracene	100	
8	10C	Aniline		100
9	23B	Quinoline	10	
10	22A	Fluorene	10	
11	22B	Fluoranthene	10	
12	82A	Cadmium	10	10
13	46A	Lead	1	
14	21B	Pyrene	1	
15	21A	2-Methylnaphthalene	1	

Run #20 Ash Stream
Flow Rate = 2.1E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	49A	Arsenic	100	1
2	54A	Selenium	1	

TABLE 8. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #21, Illinois #6

Run #21 Gas Stream
Flow Rate = 1.1E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	01B	Ethylene		10,000
2	42B	Carbon monoxide	1,000	1,000
3	53B	Hydrogen sulfide	1,000	100
4	99A	Hydrogen	100	
5	42B	Carbon dioxide	10	
6	25A	Thiophene	10	
7	13A	Methanethiol	10	
8	01A	Methane	10	10
9	53C	Carbonyl sulfide	10	
10	18A	Xylenols	10	
11	21A	Naphthalene	1	
12	53D	Carbon disulfide	1	
13	18A	Cresols	1	
14	25A	C_2-Thiophenes	1	
15	15A	Biphenyl	1	
16	18A	Phenol	1	
17	01B	Propylene		1

Run #21 Condensate Stream
Flow Rate = 1.5E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	47B	Ammonia	1,000	100,000
2	18A	Cresols	10,000	100
3	18A	Xylenols	10,000	100
4	18A	Trimethylphenol	1,000	10
5	68A	Chromium	100	10
6	49A	Arsenic	100	10
7	47A	Cyanide	1	100
8	48A	Phosphorus		100
9	53A	Thiocyanate	10	10
10	18A	Phenol	1	10
11	53A	Sulfur	1	
12	57A	Chlorides	1	

TABLE 8. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #21 Tar Stream
Flow Rate = 2.2E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	21C	Benzo(a)pyrene	10,000,000	
2	18A	Cresols	1,000,000	10,000
3	21C	Dibenzo(a,h)anthracene	1,000,000	
4	21B	Triphenylene	1,000,000	
5	18A	Xylenols	1,000,000	10,000
6	21A	Naphthalene	100	1,000,000
7	49A	Arsenic	10,000	1,000
8	21B	Benz(a)anthracene	10,000	
9	10C	Benzidine	10	10,000
10	21D	Benzo(g,h,i)perylene	1,000	
11	21A	Phenanthrene	1,000	
12	21A	9-Methylanthracene	1,000	
13	21A	Acenaphthylene	1,000	
14	18A	Phenol	100	1,000
15	23B	Acridine	1	1,000
16	21B	Chrysene	100	
17	22C	Benzo(b)Fluoranthene	100	
18	15A	Biphenyl	100	
19	21A	Acenaphthene	100	100
20	53A	Sulfur	100	
21	22D	Indeno(1,2,3-cd)pyrene	100	
22	10C	Aniline		100
23	21C	Benzo(e)pyrene	10	
24	25B	Benzothiophene	10	
25	23B	Quinoline	10	
26	22A	Fluorene	10	
27	22B	Fluoranthene	10	
28	22C	Benzo(k)fluoranthene	10	
29	82A	Cadmium	10	10
30	23C	Carbazole	1	
31	22B	Benzo(a)fluorene	1	
32	21A	C_2-(Alkyl)naphthalene	1	
33	21A	2-Methylnaphthalene	1	
34	21B	Pyrene	1	
35	22B	Benzo(b)fluorene	1	
36	24B	Dibenzofuran	1	
37	46A	Lead	1	

Run #21 Ash Stream
Flow Rate = 9.3E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	68A	Chromium	1,000	10
2	49A	Arsenic	10	1
3	32A	Beryllium	1	

TABLE 9. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #23, Illinois #6

Run #23 Gas Stream
Flow Rate = 1.6E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	1,000	1,000
2	15A	Benzene	1,000	1,000
3	53B	Hydrogen sulfide	100	100
4	99A	Hydrogen	10	
5	42B	Carbon dioxide	10	
6	01A	Methane	10	10
7	53C	Carbonyl sulfide	10	
8	15A	Toluene		10
9	13A	Methanethiol	1	
10	13A	C_2H_6S	1	
11	25A	C_2-Thiophenes	1	
12	53D	Carbon disulfide	1	

Run #23 Condensate Stream
Flow Rate = 1.3E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Cresols	10,000	100
2	18A	Xylenols	10,000	100
3	68A	Chromium	100	10
4	49A	Arsenic	100	1
5	18A	Phenol	10	10

TABLE 9. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #23 Tar Stream
Flow Rate = 2.9E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	21C	Benzo(a)pyrene	10,000,000	
2	21C	Dibenzo(a,h)anthracene	1,000,000	
3	21B	Triphenylene	1,000,000	
4	10C	Benzidine	10	10,000
5	21B	Benz(a)anthracene	1,000	
6	21D	Benzo(g,h,i)perylene	1,000	
7	21A	Acenaphthylene	100	
8	15A	Biphenyl	100	
9	22C	Benzo(b)fluoranthene	100	
10	21A	Acenaphthene	100	100
11	22D	Indeno(1,2,3-cd)pyrene	10	
12	21C	Benzo(e)pyrene	10	
13	25D	Benzothiophene	10	
14	22C	Benzo(k)fluoranthene	1	
15	23C	Carbazole	1	
16	22B	Benzo(a)fluorene	1	
17	21A	C_2-(Alkyl)naphthalene	1	
18	46A	Lead	1	
19	22B	Benzo(b)fluorene	1	

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Run #23 Ash Stream
Flow Rate = 1.4E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	68A	Chromium	1,000	10
2	49A	Arsenic	10	1
3	32A	Beryllium	1	
4	54A	Selenium	1	

TABLE 10 . POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #25, Montana Rosebud

Run #25 Gas Stream
Flow Rate = 2.3E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	1,000	1,000
2	53B	Hydrogen sulfide	1,000	1,000
3	15A	Benzene	1,000	1,000
4	47B	Ammonia	10	1,000
5	25A	Thiophene	100	
6	42B	Carbon dioxide	100	
7	15A	Toluene	1	100
8	99A	Hydrogen	10	
9	53C	Carbonyl sulfide	10	
10	53D	Carbon disulfide	10	
11	21A	Naphthalene	10	
12	13A	Methanethiol	10	
13	01A	Methane	10	1
14	18A	Cresols	1	
15	15A	Biphenyl	1	
16	15A	Diphenylmethane	1	
17	18A	Phenol	1	
18	15B	Indene	1	

Run #25 Condensate Stream
Flow Rate = 7.2E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	47B	Ammonia	1,000	100,000
2	18A	Cresols	10,000	100
3	18A	Xylenols	1,000	10
4	68A	Chromium	1,000	10
5	47A	Cyanide	10	1,000
6	18A	Phenol	10	100
7	48A	Phosphorus		100
8	53A	Thiocyanate	10	10
9	53A	Sulfur	1	

TABLE 10. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #25 Tar Stream
Flow Rate = 2.4E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	21C	Perylene	10,000,000	
2	21C	Benzo(a)pyrene	10,000,000	
3	18A	Cresols	1,000,000	10,000
4	21C	Dibenzo(a,h)anthracene	1,000,000	
5	18A	Xylenols	1,000,000	10,000
6	21B	Triphenylene	1,000,000	
7	18A	Trimethylphenol	1,000,000	10,000
8	18A	O-Isopropylphenol	1,000,000	1,000
9	21A	Naphthalene	10	100,000
10	68A	Chromium	10,000	1,000
11	21B	Benz(a)anthracene	10,000	
12	21D	Benzo(g,h,i)perylene	1,000	
13	21A	Phenanthrene	1,000	
14	21A	Acenaphthylene	1,000	
15	18A	Phenol	100	1,000
16	21A	Acenaphthene	100	1,000
17	10C	Benzidine	10	1,000
18	23B	Acridine	1	1,000
19	21B	Chrysene	100	
20	15A	Biphenyl	100	
21	22C	Benzo(b)fluoranthene	100	
22	22D	Indeno(1,2,3-cd)pyrene	100	
23	10C	Aniline		100
24	21C	Benzo(e)pyrene	10	
25	82A	Cadmium	10	10
26	23B	Quinoline	10	
27	22B	Fluoranthene	10	
28	21A	Anthracene	10	
29	23C	Carbazole	10	
30	22B	Benzo(a)fluorene	10	
31	22C	Benzo(k)fluoranthene	10	
32	25B	Benzothiophene	1	
33	21A	C_2-(Alkyl)naphthalene	1	
34	21B	Pyrene	1	
35	22B	Benzo(b)fluorene	1	
36	21A	1-Methylnaphthalene	1	
37	21A	2-Methylnaphthalene	1	
38	24B	Dibenzofuran	1	

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Run #25 Ash Stream
Flow Rate = 1.0E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	68A	Chromium	1,000	10
2	32A	Beryllium	1	

TABLE 11 . POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #26, Montana Rosebud

Run #26 Gas Stream
Flow Rate = 1.5E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	10,000	1,000
2	15A	Benzene	100	1,000
3	53B	Hydrogen sulfide	100	10
4	99A	Hydrogen	10	
5	42B	Carbon dioxide	10	
6	53C	Carbonyl sulfide	10	
7	47B	Hydrogen cyanide	10	
8	01A	Methane	10	1
9	15A	Toluene		10
10	25A	Thiophene	1	
11	18A	Xylenols	1	
12	18A	Phenol	1	
13	25A	C_2-Thiophenes	1	

Run #26 Condensate Stream
Flow Rate = 1.2E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	68A	Chromium	1,000	100
2	82A	Cadmium	1	1

TABLE 11. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #26 Tar Stream
Flow Rate = 3.4E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	21C	Perylene	100,000,000	
2	18A	Cresols	1,000,000	
3	18A	Xylenols	100,000	1,000
4	18A	Trimethylphenol	100,000	1,000
5	21A	Naphthalene	10	100,000
6	21A	Phenanthrene	1,000	
7	18A	Phenol	100	1,000
8	23B	Acridine		1,000
9	21B	Chrysene	100	
10	21A	9-Methylanthracene	100	
11	53A	Sulfur	10	
12	23B	Quinoline	10	
13	22A	Fluorene	10	
14	22B	Fluoranthene	10	
15	21A	Anthracene	10	
16	10C	Aniline		10
17	21A	2-Methylnaphthalene	1	
18	21B	Pyrene	1	
19	24B	Dibenzofuran	1	

Run #26 Ash Stream
Flow Rate = 1.3E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	68A	Chromium	1,000	100
2	32A	Beryllium	1	

TABLE 12. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run # 32, Wyoming Sub-bituminous

Run #32 Gas Stream
Flow Rate = 2.2E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	10,000	1,000
2	15A	Benzene	1,000	1,000
3	53B	Hydrogen sulfide	100	10
4	47B	Ammonia	1	100
5	15A	Toluene	1	100
6	53C	Carbonyl sulfide	10	
7	99A	Hydrogen	10	
8	42B	Carbon dioxide	10	
9	01A	Methane	10	10
10	25B	Thiophene	10	
11	47B	Hydrogen cyanide	10	
12	18A	Xylenols	1	
13	13A	Methanethiol	1	
14	18A	Phenol	1	
15	21A	Naphthalene	1	
16	15A	Xylenes	1	
17	18A	Cresols	1	
18	15A	Biphenyl	1	

Run #32 Condensate Stream
Flow Rate = 8.4E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Cresols	100,000	1,000
2	18A	Xylenols	10,000	100
3	18A	Phenol	100	1,000
4	47B	Hydrogen cyanide	10	1,000
5	68A	Chromium	100	10

TABLE 12. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #32 Tar Stream
Flow Rate = 2.2E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	21C	Perylene	10,000,000	
2	18A	Cresols	1,000,000	10,000
3	18A	Xylenols	1,000,000	10,000
4	18A	Trimethylphenol	100,000	1,000
5	18A	O-Isopropylphenol	100,000	100
6	21A	Naphthalene	10	100,000
7	68A	Chromium	10,000	100
8	18A	Phenol	100	1,000
9	23B	Acridine		1,000
10	21A	Phenanthrene	100	
11	21B	Chrysene	100	
12	46A	Lead	10	
13	21A	Anthracene	10	
14	10C	Aniline		10
15	22B	Fluoranthene	10	
16	21A	9-Methylanthracene	10	
17	22A	Fluorene	10	
18	23B	Quinoline	1	
19	21B	Pyrene	1	
20	21A	2-Methylnaphthalene	1	

Run #32 Ash Stream
Flow Rate = 8.6E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
		None		

TABLE 13 . POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #33, Wyoming Sub-bituminous

Run #33 Gas Stream
Flow Rate = 2.1E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	10,000	1,000
2	15A	Benzene	1,000	1,000
3	53B	Hydrogen sulfide	100	10
4	18A	Xylenols	100	
5	15A	Toluene	1	100
6	99A	Hydrogen	10	
7	18A	Phenol	10	
8	53C	Carbonyl sulfide	10	
9	01A	Methane	10	10
10	42B	Carbon dioxide	10	
11	18A	Cresols	10	
12	13A	Methanethiol	10	
13	15B	Indene	10	
14	15A	Biphenyl	1	
15	21A	Naphthalene	1	
16	15A	Diphenylmethane	1	

Run #33 Condensate Stream
Flow Rate = 8.0E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Cresols	100,000	1,000
2	18A	Xylenols	10,000	100
3	68A	Chromium	100	10
4	18A	Phenol	10	100
5	82A	Cadmium	1	1

TABLE 13 . POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #33 Tar Stream
Flow Rate = 2.5E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Xylenols	1,000,000	10,000
2	21C	Perylene	1,000,000	
3	21C	Benzo(a)pyrene	1,000,000	
4	18A	Cresols	1,000,000	10,000
5	18A	Trimethylphenol	1,000,000	10,000
6	18A	O-Isopropylphenol	100,000	100
7	21B	Triphenylene	100,000	
8	68A	Chromium	100,000	1,000
9	21C	Dibenzo(a,h)anthracene	100,000	
10	21A	Naphthalene	10	100,000
11	18A	Phenol	1,000	1,000
12	21B	Benz(a)anthracene	1,000	
13	10C	Benzidine	10	1,000
14	21A	Acenaphthylene	100	
15	21A	Phenanthrene	100	
16	15A	Biphenyl	100	
17	21D	Benzo(g,h,i)perylene	100	
18	21A	Acenaphthene	100	100
19	21B	Chrysene	100	
20	10C	Aniline		100
21	23B	Acridine		100
22	22C	Benzo(b)fluoranthene	10	
23	21A	Anthracene	10	
24	22A	Fluorene	10	
25	21C	Benzo(e)pyrene	10	
26	21A	9-Methylanthracene	10	
27	23B	Quinoline	1	
28	82A	Cadmium	1	1
29	46A	Lead	1	
30	25B	Benzothiophene	1	
31	22D	Indeno(1,2,3-cd)pyrene	1	
32	22B	Fluoranthene	1	
33	21A	C_2-(Alkyl)naphthalene	1	
34	21A	2-Methylnaphthalene	1	
35	23C	Carbazole	1	
36	22B	Benzo(a)fluorene	1	
37	21A	1-Methylnaphthalene	1	
38	22C	Benzo(k)fluoranthene	1	
39	22B	Benzo(b)fluorene	1	

Run #33 Ash Stream
Flow Rate = 8.3E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
		None		

TABLE 14. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #35, Wyoming Sub-bituminous

Run #35 Gas Stream
Flow Rate = 2.4E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	1,000	1,000
2	21B	$C_{16}H_{10}$: 4 rings	1,000	
3	15A	Benzene	1,000	1,000
4	15A	Toulene	1	100
5	99A	Hydrogen	10	
6	42B	Carbon dioxide	10	
7	18A	Xylenols	10	
8	53C	Carbonyl sulfide	10	
9	18A	Phenol	10	
10	13A	Methanethiol	10	
11	53B	Hydrogen sulfide	10	10
12	01A	Methane	10	1
13	18A	Cresols	10	
14	25A	Thiophene	1	
15	15B	Indene	1	
16	15A	Biphenyl	1	

Run #35 Condensate Stream
Flow Rate = 7.7E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Cresols	100,000	1,000
2	18A	Xylenols	10,000	100
3	18A	Phenol	100	1,000
4	82A	Cadmium	1	1

TABLE 14. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #35 Tar Stream
Flow Rate = 5.9E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Cresols	10,000,000	100,000
2	18A	Xylenols	1,000,000	10,000
3	21C	Perylene	1,000,000	
4	18A	Trimethylphenol	100,000	1,000
5	21C	Benzo(a)pyrene	100,000	
6	18A	O-isopropylphenol	100,000	100
7	21B	Triphenylene	100,000	
8	21A	Naphthalene	1	10,000
9	18A	Phenol	1,000	1,000
10	21B	Benz(a)anthracene	100	
11	15A	Biphenyl	100	
12	21A	9-methylanthracene	100	
13	21A	Acenaphthylene	100	
14	21A	Phenanthrene	100	
15	21A	Acenaphthrene	100	100
16	23B	Acridine		100
17	21B	Chrysene	10	
18	10C	Aniline		10
19	22C	Benzo(b)fluoranthene	1	
20	21A	Anthracene	1	
21	22A	Fluorene	1	
22	21A	C_2-(alkyl)naphthalene	1	
23	21A	1-methylnaphthalene	1	
24	22B	Benzo(a)fluorene	1	
25	23C	Carbazole	1	
26	22B	Benzo(b)fluorene	1	
27	25B	Benzothiophene	1	
28	21A	2-methylnaphthalene	1	

Run #35 Ash Stream
Flow Rate = 1.4E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	68A	Chromium	1,000	10
2	54A	Selenium	1	1
3	32A	Beryllium	1	

TABLE 15. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #36, North Dakota Lignite

Run #36 Gas Stream
Flow Rate = 2.0E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	10,000	1,000
2	15A	Benzene	1,000	1,000
3	53B	Hydrogen sulfide	100	10
4	15A	Toluene	1	100
5	25A	Thiophene	10	
6	13A	Methanethiol	10	
7	99A	Hydrogen	10	
8	42B	Carbon dioxide	10	
9	53C	Carbonyl sulfide	10	
10	18A	Xylenols	10	
11	13A	C_2H_6S	10	
12	01A	Methane	10	1
13	18A	Phenol	1	
14	18A	Cresols	1	
15	21A	Naphthalene	1	
16	15A	Biphenyl	1	

Run #36 Condensate Stream
Flow Rate = 9.3E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Cresols	100,000	1,000
2	47B	Ammonia	1,000	100,000
3	18A	Xylenols	10,000	100
4	47B	Hydrogen cyanide	10	1,000
5	68A	Chromium	100	1
6	18A	Phenol	100	100
7	49A	Arsenic	10	1

TABLE 15. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #36 Tar Stream
Flow Rate = 1.2E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	21C	Benzo(a)pyrene	1,000,000	
2	21C	Perylene	1,000,000	
3	18A	Cresols	1,000,000	10,000
4	21B	Triphenylene	1,000,000	
5	18A	Trimethylphenol	100,000	1,000
6	68A	Chromium	100,000	1,000
7	21C	Dibenzo(a,h)anthracene	100,000	
8	18A	Xylenols	100,000	1,000
9	18A	O-Isopropylphenol	100,000	100
10	21A	Naphthalene	1	10,000
11	21B	Benz(a)anthracene	1,000	
12	21A	Acenaphthylene	1,000	
13	10C	Benzidine	10	1,000
14	49A	Arsenic	100	10
15	18A	Phenol	100	100
16	21A	Phenanthrene	100	
17	21D	Benzo(g,h,i)perylene	100	
18	15A	Biphenyl	100	
19	21A	Acenaphthene	100	100
20	22C	Benzo(b)fluoranthene	100	
21	21B	Chrysene	100	
22	23B	Acridine		100
23	21A	Anthracene	10	
24	21C	Benzo(e)pyrene	10	
25	46A	Lead	10	
26	82A	Cadmium	10	10
27	25B	Benzothiophene	10	
28	21A	9-Methylanthracene	10	
29	22A	Fluorene	10	
30	23B	Quinoline	10	
31	22B	Fluoranthene	10	
32	22C	Benzo(k)fluoranthene	1	
33	22D	Indeno(1,2,3-cd)pyrene	1	
34	22B	Benzo(a)fluorene	1	
35	22B	Benzo(b)fluorene	1	
36	21A	1-Methylnaphthalene	1	
37	21A	C_2-(Alkyl)naphthalene	1	
38	23C	Carbazole	1	
39	21B	Pyrene	1	
40	21A	2-Methylnaphthalene	1	

Run #36 Ash Stream
Flow Rate = 8.9E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	68A	Chromium	10,000	100
2	49A	Arsenic	100	10
3	32A	Beryllium	1	

TABLE 16 . POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #38P, Illinois #6

Run #38P Gas Stream
Flow Rate = 1.9E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	21B	$C_{16}H_{10}$: 4 rings	1,000	
2	42B	Carbon monoxide	100	100
3	53B	Hydrogen sulfide	100	100
4	18A	Xylenols	100	
5	15A	Benzene	100	100
6		Toluene		100
7	13A	Methanethiol	10	
8	53C	Carbonyl sulfide	10	
9	53D	Carbon disulfide	10	
10	53B	Sulfur dioxide	10	
11	42B	Carbon dioxide	10	
12	18A	Cresols	10	
13	18A	Phenol	1	
14	13A	C_2H_6S	1	
15	15B	Indene	1	
16	25A	Thiophene	1	

Run #38P Condensate Stream
Flow Rate = 3.0E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Cresols	10,000	100
2	18A	Xylenols	10,000	100
3	18A	Phenol	1	10

TABLE 16 . POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #38P Tar Stream
Flow Rate = 1.4E-05 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Cresols	100,000	1,000
2	18A	Xylenols	100,000	1,000
3	18A	Trimethylphenol	100,000	1,000
4	18A	O-Isopropylphenol	100,000	100
5	23B	Acridine		1,000
6	21A	Naphthalene		1,000
7	21A	9-Methylanthracene	100	
8	21A	Phenanthrene	100	
9	18A	Phenol	10	100
10	10C	Aniline		100
11	21A	Anthracene	1	

Run #38P Ash Stream
Flow Rate = 1.4E-05 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
		None		

TABLE 17. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #38G, Illinois #6

Run #38G Gas Stream
Flow Rate = 7.7E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	1,000	1,000
2	53B	Hydrogen sulfide	100	100
3	15A	Benzene	100	100
4	15A	Toluene		100
5	53C	Carbonyl sulfide	10	
6	42B	Carbon dioxide	10	
7	99A	Hydrogen	10	
8	13A	Methanethiol	10	
9	53D	Carbon disulfide	10	
10	13A	C_2H_6S	10	
11	01A	Methane	1	
12	53B	Sulfur dioxide	1	1
13	25A	Thiophene	1	

Run #38G Condensate Stream
Flow Rate = 6.5E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Cresols	100,000	1,000
2	18A	Xylenols	100,000	1,000
3	18A	Phenol	10	100
4	49A	Arsenic	100	10

TABLE 17. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #38G Tar Stream
Flow Rate = 3.0E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Cresols	1,000,000	10,000
2	18A	Xylenols	1,000,000	10,000
3	18A	O-Isopropylphenol	1,000,000	1,000
4	21A	Naphthalene	1	10,000
5	18A	Phenol	100	1,000
6	21A	9-Methylanthracene	100	
7	49A	Arsenic	100	
8	21A	Phenanthrene	100	
9	21B	Chrysene	100	
10	21A	Anthracene	1	
11	23B	Quinoline	1	
12	22A	Fluorene	1	
13	22B	Fluoranthene	1	
14	21A	2-Methylnaphthalene	1	

Run #38P Ash Stream
Flow Rate = 2.2E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	49A	Arsenic	10	1

TABLE 18. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #41, West. Kentucky #9

Run #41 Gas Stream
Flow Rate = 1.1E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	1,000	1,000
2	15A	Benzene	1,000	1,000
3	53B	Hydrogen sulfide	100	100
4	15A	Toluene	1	100
5	42B	Carbon dioxide	10	
6	53C	Carbonyl sulfide	10	
7	99A	Hydrogen	10	
8	13A	C_2H_6S	10	
9	01A	Methane	10	10
10	13A	Methanethiol	10	
11	21A	Naphthalene	10	
12	18A	Phenol	10	
13	25A	Thiophene	10	
14	15A	Biphenyl	1	
15	15A	C_4-Benzene	1	
16	18A	Cresols	1	
17	15B	Indene	1	
18	25A	Methylthiophene	1	

Run #41 Condensate Stream
Flow Rate = 6.5E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Cresols	100,000	1,000
2	18A	Xylenols	10,000	100
3	18A	Phenol	10	100

TABLE 18. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #41 Tar Stream
Flow Rate = 1.8E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	21C	Benzo(a)pyrene	10,000,000	
2	18A	Cresols	1,000,000	10,000
3	21B	Triphenylene	1,000,000	
4	18A	Xylenols	1,000,000	10,000
5	18A	Trimethylphenol	100,000	1,000
6	21C	Dibenzo(a,h)anthracene	100,000	
7	18A	O-Isopropylphenol	100,000	100
8	21A	Naphthalene	10	100,000
9	21B	Benz(a)anthracene	1,000	
10	21A	Phenanthrene	1,000	
11	10C	Benzidine	10	1,000
12	23B	Acridine		1,000
13	21D	Benzo(g,h,i)perylene	100	
14	21A	Acenaphthylene	100	
15	15A	Biphenyl	100	
16	21A	9-Methylanthracene	100	
17	21A	Acenaphthene	100	100
18	22C	Benzo(b)fluoranthene	100	
19	18A	Phenol	100	100
20	21C	Benzo(e)pyrene	10	
21	21A	Anthracene	10	
22	25B	Benzothiophene	10	
23	22B	Fluoranthene	10	
24	22D	Indeno(1,2,3-cd)pyrene	10	
25	22A	Fluorene	10	
26	21B	Pyrene	10	
27	10C	Aniline		10
28	23C	Carbazole	1	
29	23B	Quinoline	1	
30	22C	Benzo(k)fluoranthene	1	
31	21A	2-Methylnaphthalene	1	
32	24B	Dibenzofuran	1	
33	22B	Benzo(a)fluorene	1	
34	21A	1-Methylnaphthalene	1	

Run #41 Ash Stream
Flow Rate = 4.8E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	49A	Arsenic	10	1
2	54A	Selenium	10	1

TABLE 19. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #43, North Dakota Lignite

Run #43 Gas Stream
Flow Rate = 2.6E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	10,000	1,000
2	15A	Benzene	100	1,000
3	15A	Toluene	1	100
4	21B	$C_{16}H_{10}$: 4 rings	100	
5	53B	Hydrogen sulfide	10	10
6	53C	Carbonyl sulfide	10	
7	99A	Hydrogen	10	
8	42B	Carbon dioxide	10	
9	13A	C_2H_6S	10	
10	01A	Methane	10	1
11	13A	Methanethiol	10	
12	18A	Cresols	1	
13	15B	Indene	1	
14	53D	Carbon disulfide	1	

Run #43 Condensate Stream
Flow Rate = 1.1E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Cresols	100,000	1,000
2	18A	Xylenols	100,000	1,000
3	18A	Phenol	100	1,000
4	21C	Benzo(a)pyrene	100	
5	21C	Perylene	100	
6	21B	Triphenylene	10	

TABLE 19 . POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #43 Tar Stream
Flow Rate = 1.8E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	18A	Xylenols	10,000,000	100,000
2	18A	Trimethylphenol	1,000,000	10,000
3	18A	Cresols	1,000,000	10,000
4	18A	O-Isopropylphenol	1,000,000	1,000
5	21C	Perylene	100,000	
6	21C	Benzo(a)pyrene	100,000	
7	21B	Triphenylene	10,000	
8	21C	Dibenzo(a,h)anthracene	10,000	
9	21A	Naphthalene	1	10,000
10	18A	Phenol	100	1,000
11	10C	Benzidine	10	1,000
12	21B	Chrysene	100	
13	21B	Benz(a)anthracene	100	
14	15A	Biphenyl	100	
15	21A	Acenaphthylene	100	
16	21A	Phenanthrene	100	
17	21A	Acenaphthene	100	100
18	23B	Acridine		100
19	21D	Benzo(g,h,i)perylene	10	
20	21A	Anthracene	10	
21	22A	Fluorene	10	
22	21A	9-Methylanthracene	1	
23	23C	Carbazole	1	
24	21A	C_2-(Alkyl)Naphthalene	1	
25	22C	Benzo(b)fluoranthene	1	
26	25B	Benzothiophene	1	
27	21A	1-Methylnaphthalene	1	
28	21A	2-Methylnaphthalene	1	
29	22B	Fluoranthene	1	
30	23B	Quinoline	1	
31	10C	Aniline		1

Run #43 Ash Stream
Flow Rate = 2.2E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
		None		

TABLE 20 . POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #44, Illinois #6

Run #44 Gas Stream
Flow Rate = 1.2E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	1,000	1,000
2	15A	Benzene	1,000	1,000
3	53B	Hydrogen sulfide	100	100
4	53C	Carbonyl sulfide	100	
5	21B	$C_{16}H_{10}$: 4 rings	100	
6	15A	Toluene	1	100
7	42B	Carbon dioxide	10	
8	99A	Hydrogen	10	
9	25A	Thiophene	10	
10	13A	C_2H_6S	10	
11	01A	Methane	10	1
12	25A	Methylthiophene	1	
13	53D	Carbon disulfide	1	
14	15B	Indene	1	
15	13A	Methanethiol	1	

Run #44 Condensate Stream
Flow Rate = 6.5E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
		None		

TABLE 20 . POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY (continued)

Run #44 Tar Stream
Flow Rate = 1.8E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	21C	Perylene	10,000,000	
2	18A	Xylenols	100,000	1,000
3	18A	Cresols	100,000	1,000
4	21A	Naphthalene	10	100,000
5	18A	Trimethylphenol	10,000	100
6	21B	Chrysene	1,000	
7	23B	Acridine		1,000
8	21A	Phenanthrene	100	
9	21A	9-Methylanthracene	100	
10	18A	Phenol	10	100
11	21A	Anthracene	10	
12	22B	Fluoranthene	10	
13	22A	Fluorene	10	
14	21B	Pyrene	10	
15	23B	Quinoline	1	
16	24B	Dibenzofuran	1	
17	21A	2-Methylnaphthalene	1	

Run #44 Ash Stream
Flow Rate = 1.5E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	49A	Arsenic	100	1

TABLE 21. POTENTIAL ENVIRONMENTAL POLLUTANTS RANKED VIA DISCHARGE SEVERITY
Run #45, Wyoming Sub-bituminous

Run #45 Gas Stream
Flow Rate = 4.6E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	42B	Carbon monoxide	10,000	1,000
2	15A	Benzene	1,000	1,000
3	53B	Hydrogen sulfide	100	10
4	15A	Toluene	1	100
5	53C	Carbonyl sulfide	10	
6	99A	Hydrogen	10	
7	42B	Carbon dioxide	10	
8	01A	Methane	10	1
9	13A	Methanethiol	10	
10	25A	Thiophene	1	
11	13A	C_2H_6S	1	

- -

Run #45 Condensate Stream
Flow Rate = 1.7E-01 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
		None		

- -

Run #45 Tar Stream
Flow Rate = 7.9E-03 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
		None		

- -

Run #45 Ash Stream
Flow Rate = 2.5E-02 g/sec

Rank	MEG Category	Compound	Discharge Severity (Health)	Discharge Severity (Ecology)
1	68A	Chromium	1,000	10
2	54A	Selenium	10	1
3	32A	Beryllium	1	

magnitude of 1000. These species included benzene, and pyrene, H_2S. Although the Illinois No.6 coal was primarily responsible for these constituents, the pyrene was also found to occur with the North Dakota lignite and Wyoming subbituminous while the H_2S occurred at this same relative concentration for the Western Kentucky No.9 coal. A number of other sulfur-containing species were also found at DS values between 1 and 100 including thiophene, methanethiol, and ethanethiol.

In the aqueous condensate stream from the screening test runs it was found that cresols and xylenols were most predominant in their discharge severity values. These species occurred at an order of magnitude of 100,000. The values were high for all of the coals tested. The cresol values were at the maximum order of magnitude level for Illinois No.6, Western Kentucky No.9, Wyoming subbituminous coal as well as North Dakota lignite. The xylenols were at this maximum value for both the Illinois No.6 coal and the North Dakota lignite. The element, chromium, was also detected at a significant discharge severity level in the aqueous condensate stream, i.e., 10,000. This should be regarded as an artifact of the laboratory gasifier system since the stainless steel reactor tube can be regarded as being responsible for such high chromium levels. The other significant compounds found in the aqueous condensate stream were ammonia and trimethylphenol at discharge severity order of magnitude value of 1,000; benzo(a)pyrene, perylene, phenol, and arsenic at discharge severity order of magnitudes of 100; triphenylene, cyanide, thiocyanate, cadmium and lead at discharge severity order of magnitude values of 10.

The order of magnitude values which predominated in the gasifier tar stream were perylene, benzo(a)pyrene, and phenolic compounds. Perylene occurred at sufficiently high concentrations to provide a discharge severity of 10^8 for Montana Rosebud coal. The DS value for this compound was 10^7 for Illinois No.6 coal. Benzo(a)pyrene gave rise to an order of magnitude 10^7 for Illinois No.6, Western Kentucky No.9, and Montana Rosebud coal while a value of 10^6 was obtained for North Dakota lignite. The order of magnitude of the discharge severities for both cresols and xylenols was 10^7 for Wyoming subbituminous coal and North Dakota lignite, respectively. The cresols were found at a DS ranking of 10^6 for Illinois No.6 and Montana Rosebud coal while the xylenols were found at a ranking of 10^6 for both Western Kentucky No.9 and Wyoming subbituminous coal.

Four compounds were found in gasifier tar streams at discharge severity order of magnitude 10^6. These include triphenylene, dibenzo(a,h)anthracene, trimethylphenol, and o-isopropylphenol. Both chromium and arsenic were found at high orders of magnitude. The arsenic was found at DS value of 10,000 while the chromium should be discounted since the laboratory reactor stainless steel contained substantial chromium which was undoubtedly contributed to the products of reaction. A large number of other organic species were also found at significant values in the gasifier tar stream. These include benz(a)anthracene, acenaphthylene, phenanthrene, 9-methylanthracene, benzo(g,h,i)perylene, chrysene, and phenol.

The solid residue resulting from the gasification process may be referred to as an ash since the reactor bed is exposed to oxidation conditions at the air inlet. The solid residue stream was determined to contain three elements which exceeded their DMEG values. These include chromium, arsenic, and selenium. However, the substantial chromium content must be regarded as an artifact due to erosion of the gasification reactor itself. Arsenic was determined at a discharge severity (health) level of 100 for Illinois No.6, Western Kentucky No.9 and Pittsburgh No.8 coals as well as the North Dakota lignite. Selenium was also found at a DS level of 10 in residue from Illinois No.6 and Western Kentucky No.9 gasification test runs. (Only a few results have been presented in this work for the Pittsburgh No.8 seam coal. This is due to the fact that it was not possible to successfully gasify this highly caking coal in the RTI fixed-bed gasifier without pretreatment.)

4.3 ECOLOGY-BASED RESULTS

Tables 5 through 21 also present discharge severity (ecology) results which were computed by dividing the effluent stream concentrations as shown in the Appendix by the corresponding DMEG (ecology) values. Since the data base of DMEG (ecology) values is somewhat less extensive than the corresponding DMEG (health) compilation, then the number of compounds for which results can be reported is therefore less.

In the gasifier effluent gas stream, it was found that ethylene gave rise to the highest DS (ecology) value, which was 10,000. At an order of magnitude 1,000 was the compounds carbon monoxide, H_2S, benzene, toluene, and ammonia. For the aqueous condensate stream, ammonia give rise to the highest DS (ecology) value, which was 100,000. At an order of magnitude of 1,000 were cresols, xylenols, trimethylphenol, and cyanide.

A substantially larger number of compounds were found in the gasifier tar stream which exceeded their DMEG (ecology) values. At an order of magnitude of 1,000,000 was naphthalene while cresols and xylenols were found at an order of magnitude of 100,000. This was followed by trimethylphenol and benzidine, which possessed an order of magnitude of 10,000. The additional compounds occurring at DS values of 10 to 1,000 in order of magnitude included phenol, isopropylphenol, biphenyl, acenaphthene, benzo(k)fluoranthene, aniline, acridine, as well as the trace metals, arsenic, cadmium, and chromium. Again, the chromium must be regarded as an artifact being derived from the stainless steel metal which constituted the gasifier reactor shell. The gasification residue in addition to chromium was found to contain arsenic at a DS (ecology) value of the order of magnitude 10.

The results of this evaluation of the environmental potential for ecological effects were found to be generally true for all the coals tested. The North Dakota lignite was found to give high values for ammonia, cyanide, and phenolic compounds, e.g., xylenols. High values were also obtained from the eastern high volatile coals including the Illinois No.6 and Western Kentucky No.9 coals. The Wyoming subbituminous coal was often found to give rise to somewhat lower concentrations of the important species in the gasification reactor effluent streams.

4.4 OTHER FINDINGS

The highest species concentrations in the reactor gas stream were found to be contributed by carbon monoxide, methane, and hydrogen. These concentrations were 3.0×10^8, 3.6×10^7, and 2.7×10^7 $\mu g/m^3$, respectively. The concentrations for hydrogen sulfide, benzene, and thiophene which were 1.7×10^7, 3.3×10^6, and 2.3×10^6 $\mu g/m^3$. Maximum liquid discharge concentrations were found for phenol, cresols, and xylenols at 2.8×10^6,

1.5×10^6, 1.5×10^6, and 3.7×10^5 μg/l, respectively. Methylnaphthalenes were detected in aqueous condensate at 7.0×10^2 while chrysene, phenanthrene, acenaphthene, and fluorene were determined at maximum concentrations of 160, 96, 57, and 57 μg/l, respectively. Inorganic species in the aqueous condensate were found at maximum values for ammonia, cyanide, and thiocyanate at 7.9×10^6, 1.0×10^6, and 2.7×10^5 μg/l, respectively.

Maximum concentrations determined in gasifier tar from the RTI laboratory gasifier were determined for xylenols, cresols, and trimethylphenol at concentration values of 1.2×10^5, 6.7×10^4 and 2.4×10^4 μg/g, respectively. Additional compounds at maximum concentrations in the gasifier tar were naphthalene, benzofluorene, pyrene, phenanthrene, and anthracene at concentrations of 5.7×10^4, 3.4×10^4, 2.4×10^4, 2.3×10^4, and 2.3×10^4 μg/g, respectively.

The actual quantity of hydrogen sulfide and carbonyl sulfide generated per unit gram of carbon converted during the gasification process were determined for each of the coals gasified. The Western Kentucky No.9 coal gave rise to 4.0×10^4 and 8.5×10^2 μg of each of these species per gram of carbon converted, respectively. The production factors for hydrogen sulfide from the other coals were less by at least one order of magnitude depending upon the sulfur content of the coal in question. For example, 3.8×10^3 and 4.9×10^2 were the production factors for hydrogen sulfide for Illinois No.6 coal and North Dakota lignite, respectively. The carbonyl sulfide values for these two coals were 4.0×10^2 and 3.7×10^2, respectively. Thus, it was found that the hydrogen sulfide production level was directly related to the sulfur content of the feed coal while the carbonyl sulfide level was lower but of essentially the same magnitude for each of the coals gasified.

Production factors for phenol varied from 4.3×10^2 to 1.4×10^3 μg of phenol/g of carbon converted for Illinois No.6 and North Dakota lignite feed materials, respectively. The production level of benzene, toluene, and xylenes, was effectively the same order of magnitude for both Illinois No.6 coal and North Dakota lignite, respectively, being of the order of 10,000 μg/g of carbon converted. Further, it was found that the production factors for naphthalene were of the order of 1,000 μg/g of carbon converted for both Illinois No.6 and Western Kentucky No.9 coals while for western coals, this value was of the order of 600 μg/g of carbon converted. In fact, the production factors for naphthalene and higher polycyclic aromatic hydrocarbons were found to depend upon reactor operating temperatures to a somewhat greater degree than for other species studied.

5.0 BIOASSAY RESULTS

The bioassay studies which have been conducted as a part of this project include both the Ames mutagenicity assay and the Chinese hamster ovary cell culture in both the growth kinetics and clonal efficiency modes. The environmentally significant samples which were tested include raw coal dusts, crude gasifier tars, tar partitions, aqueous condensate from gasification, and volatile organics collected on XAD-2 resin.

5.1 COAL DUST BIOASSAYS

Results of the Ames bioassay for raw coal dust samples are presented in Table 22. North Dakota lignite, Wyoming subbituminous coal, Western Kentucky No.9 coal, and Illinois No.6 coal were prepared in dust form at -74 microns. These dust samples were ultrasonically dispersed in the Ames bioassay medium using a procedure previously developed for flyash samples. Since no mutagenic ratio exceeded 3 it is concluded that these dust samples tested negative using both the TA 98 and TA 100 bacterial strains with and without S-9 activation. Moreover, the viability ratio provides evidence that the cells were capable of surviving exposure to the coal particles in order to give meaningful results. Only in the dust of North Dakota lignite was a toxicity found of the Salmonella to the raw coal. This phenomenon occurred for both the TA 98 and TA 100 bacterial strains; a phenomenon which was found to be much less significant for those samples containing S-9 activation. Hence, the raw coals were found to be nonmutagenic at doses to 10 mg/plate.

These coal dust samples were also subjected to CHO growth kinetics and clonal efficiency assays. Figure 4 displays a control culture of CHO cells at 140X magnification. This can be compared to Figure 5 in which CHO cells were subjected to Upper Freeport coal dust at 10 mg/ml. Here it is seen that the CHO cells have ingested the coal particles. It is believed that the classical phenomenon known as pinocytosis has taken place in which the CHO cells have surrounded and engulfed the coal particles. In spite of this incorporation process, the raw coal dusts were found to be noncytotoxic to doses as high as 10 mg/ml.

TABLE 22. AMES BIOASSAY RESULTS FOR RAW COAL DUST SAMPLES

Coal Type	Dose µg/plate	Viability Ratio				Mutagenic Ratio			
		TA 98		TA 100		TA 98		TA 100	
		+MA	-MA	+MA	-MA	+MA	-MA	+MA	-MA
North Dakota	1000	.002	.000	.045	.004	.525	.571	.492	.285
Lignite	500	.030	.000	.344	.009	.650	.500	.615	.281
	250	.126	.003	.319	.004	.750	.392	.738	.251
	100	.557	.000	.795	.000	.800	.678	.665	.372
	10	.796	.879	.114	.060	.800	.857	.896	.779
Wyoming	1000	.835	.156	.786	.328	.850	.821	1.16	.852
Sub-bituminous	500	.895	.819	.680	.342	.975	1.03	1.19	.900
	250	.868	.865	.844	.310	1.07	1.17	1.30	.917
	100	1.02	.826	.827	.328	.975	1.00	1.18	.900
	10	.994	1.00	.872	.162	.950	1.03	1.15	.948
Western Kentucky #9	1000	.91	.08	1.20	1.69	.810	1.03	.93	.94
Bituminous	500	.93	.82	1.12	1.48	.900	.980	.92	1.10
	250	.74	.84	1.31	1.27	.880	1.05	1.00	1.04
	100	.88	.76	1.29	1.39	.800	1.13	1.03	1.07
	10	.87	.80	1.17	1.44	.840	1.19	1.03	1.06
Illinois #6	1000	.934	1.18	.602	.467	1.03	1.03	1.12	1.07
Bituminous	500	.887	.989	.508	.245	.975	.857	.83	1.06
	250	.793	1.08	.475	.226	.975	1.00	.72	--
	100	.653	.517	.413	.143	.800	1.25	.95	1.12
	10	.953	.776	.266	.277	.975	.928	.90	1.04

NOTE: +MA is with S-9 activation, -MA is without such activation.

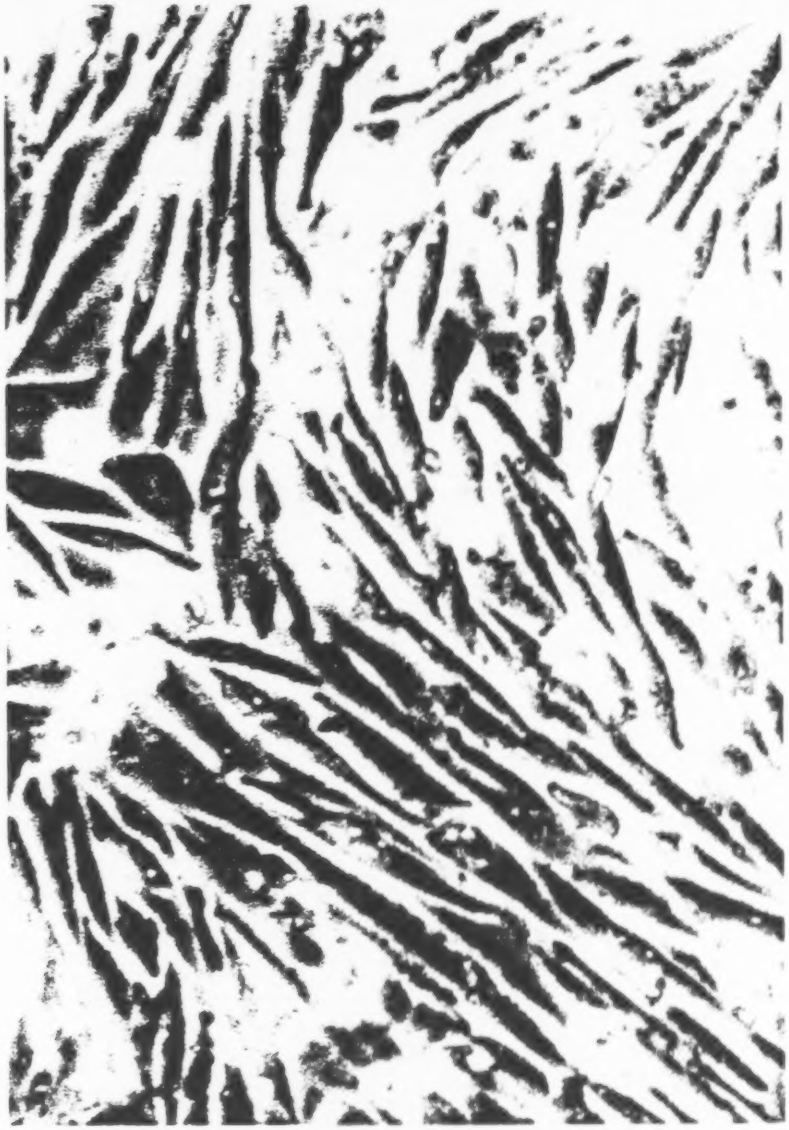


Figure 4. Chinese hamster ovary cells in culture, control sample (25 μg DMSO). (Magnification: 140x).

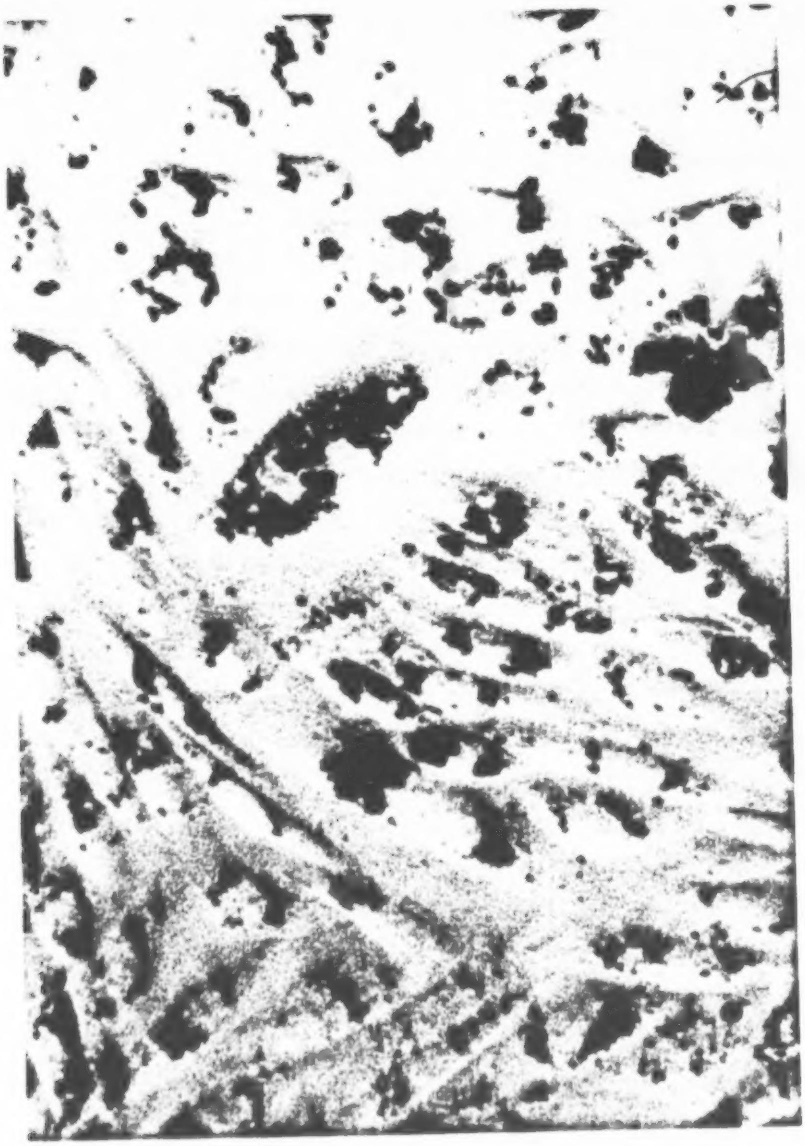


Figure 5. Chinese hamster ovary cells in culture, Upper Freeport coal dust sample (10 mg/ml). Magnification: 140x).

The low and medium designations provided on Figure 23 represent extrapolations of the available data so as to account for higher dose levels; high doses were not achieved since the capacity of the DMSO for coal dust was limited. High, medium, and low designations indicate that the maximum acceptable dose (50 percent inhibition level) is achieved at levels of 0.1 mg or less, 0.11 to 9.99 mg, and 10 mg or more.

5.2 EFFLUENT BIOASSAYS (AMES)

Initially Ames bioassay tests were conducted with bacterial strains TA 98, 100, 1535, 1537, and 1538. The TA 98 and 100 strains represent the equivalent of TA 1538 and 1535, respectively, with PK 101 plasmid for ampicillin resistance. These strains were employed both with and without S-9 activation. Early test results indicated that no additional information was gained through the use of all five strains. Therefore, strains TA 98 and 100 were used exclusively in the subsequent Ames assays.

Tables 24 and 25 present dose response information for the Western Kentucky No.9 and Wyoming subbituminous coal related samples, respectively. These tables contain both viability ratios and mutagenicity ratios for bacterial strains TA 98 and 100. Samples were assayed both with and without S-9 activations. It can be seen in Table 24 that phenocopies resulted in three samples. For these samples changes of a nonmutagenic nature occurred in the laboratory which mask the desired phenomenon.

Figure 6 displays photographs of Ames bioassay plates used for control and standard compound testing. Also shown is a plate to which the acid partition from a crude tar derived from Wyoming subbituminous coal was tested. For this plate, it can be seen that a negative result is achieved as compared with the lower plate on which 2-aminoanthracene was tested.

The Ames bioassay plate which resulted from testing the PNA fraction of crude tar associated with the gasification of Illinois No.6 is shown in Figure 7. Doses of 25 and 500 mg/plate of PNA samples are shown as well as S-9 doses of 1.5, 3.0, and 6.0 mg/plate. A value of 3.0 mg of S-9 per plate was found to be optimal in this study for the samples under examination. The organic base fraction from the crude tar resulting from the gasification of Wyoming subbituminous coal was tested on Ames bioassay plates as shown in the Figure 8. Utilizing an S-9 concentration of 3.0 mg/plate a dose-response relationship for the organic base fraction was achieved. As shown the three

TABLE 23. CHINESE HAMSTER OVARY CELL BIOASSAY RESULTS ON RAW COAL DUST SAMPLES

COAL TYPE	µg/2ml	Growth Kinetics % Inhibition	Clonal Efficiency % Inhibition
North Dakota	125	20 (medium)	11 (medium)
Lignite	50	2 (low)	67 (medium)
Wyoming	250	10 (low)	33 (medium)
Subbituminous	100	50 (medium)	2 (low)
Western Kentucky #9	250	0 (none)	13 (medium)
Bituminous	100	0 (none)	11 (medium)
Illinois #6	250	0 (none)	22 (medium)
Bituminous	100	0 (none)	20 (medium)
Pittsburgh #8	250	28 (medium)	7 (low)
(West Virginia)	100	10 (low)	0 (none)
Upper Freeport	250	0 (none)	0 (none)
(Pennsylvania)	100	0 (none)	0 (none)
Mary Lee	250	0 (none)	0 (none)
(Alabama)	100	0 (none)	8 (none)

TABLE 24. AMES BIOASSAY RESULTS FOR COAL GASIFIER EFFLUENTS

Coal Type: Western Kentucky #9

Sample	Dose µg/plate	Viability Ratio				Mutagenic Ratio			
		TA 98		TA 100		TA 98		TA 100	
		+MA	-MA	+MA	-MA	+MA	-MA	+MA	-MA
Crude Tar	1000	.01	.01	.01	.02	.1	.7	.0	.4
	500	.01	.01	.01	.01	2.7	Phenocopies	.5	1.1
	250	.25	.01	3.94	.01	3.9	.4	1.2	.5
	100	.77	.23	.88	.01	8.8	.8	1.5	.6
	10	1.03	.91	1.10	.07	4.4	.9	1.6	.9
Water Condensate	1000	1.28	1.10	1.14	.96	1.0	.8	1.1	1.0
	500	1.28	1.10	1.04	.96	1.0	1.0	1.0	1.0
	250	1.20	1.05	.96	.89	.9	.8	1.1	1.0
	100	1.15	1.04	1.02	.90	.9	.9	.8	1.0
	10	.97	1.03	.87	.98	.9	1.0	1.0	.9
PNA	1000	.01	.00	.00	.00	26.4	Phenocopies	2.3	1.0
	500	.14	.04	.07	.02	24.5	Phenocopies	2.3	.9
	250	.54	.19	.50	.05	23.8	3.6	2.4	.6
	100	.88	.60	.99	.44	9.5	2.2	2.0	.7
	10	1.02	.92	.99	.74	2.4	1.2	1.2	.9
PN	1000	.61	.06	--	--	9.0	.8	--	--
	500	1.00	.19	.72	.02	9.8	.8	2.2	.5
	250	.97	.73	1.00	.10	3.9	.9	2.0	.9
	100	1.00	1.07	1.00	.75	1.2	.8	1.7	1.0
	10	1.02	.91	1.00	.88	.8	.7	1.0	1.0
Acids	500	.00	.00	.00	.00	.2	1.0	.6	.0
	250	.58	.00	.72	.01	1.6	.2	.9	1.2
	100	.73	.68	1.07	.30	1.5	.8	1.5	1.0
	10	.86	.48	1.04	.53	1.4	.9	1.6	1.0

NOTE: +MA is with S-9 activation, -MA is without such activation.

Table 24. con't.

Sample	Dose µg/plate	Viability Ratio TA 98 +MA	Viability Ratio TA 98 -MA	Viability Ratio TA 100 +MA	Viability Ratio TA 100 -MA	Mutagenic Ratio TA 98 +MA	Mutagenic Ratio TA 98 -MA	Mutagenic Ratio TA 100 +MA	Mutagenic Ratio TA 100 -MA
Bases	500	.12	.06	.14	.00	16.4	.1	.9	1.4
	250	.64	1.02	.55	.14	15.1	.3	5.5	.8
	100	.76	.66	1.03	.55	17.2	1.0	8.6	1.1
	10	.74	1.03	1.26	.81	9.2	1.0	6.5	1.1
	1	.90	1.19	1.03	.82	1.8	1.0	1.18	1.0
NPN	1000	.05	.11	.01	.00	.8	.3	1.0	.9
	500	.36	.08	.09	.00	.7	.2	1.2	1.1
	250	.51	.26	.44	.04	1.0	.1	1.5	.6
	100	.86	.38	1.07	.005	1.5	.5	1.6	1.0
	10	.96	1.00	1.11	.50	1.1	.6	1.6	1.4
Cyclohexane Insolubles	1000	.32	.00	.22	.00	.8	.9	1.4	.8
	500	.32	.00	1.17	.89	2.4	.2	2.7	1.5
	250	.66	.00	.91	.02	3.1	.2	2.1	1.0
	100	.90	.33	1.30	.56	2.4	.5	1.6	1.4
	10	.81	1.22	1.00	1.00	1.1	.9	.9	1.6
XAD Steady State	5000	.00	.00	.00	.00	.7	.9	.4	.0
	1000	1.03	.00	2.43	1.61	1.2	.9	1.1	.9
	500	1.20	.01	2.60	2.17	1.2	.9	1.1	.9
	250	1.21	.82	2.55	2.50	1.2	1.1	1.0	1.1
	125	1.20	.93	2.64	2.30	1.2	1.2	1.0	.9
XAD Surge	5000	.00	.00	.00	.00	1.2	1.0	.2	.0
	1000	.00	.00	.71	.01	.6	.6	.8	.3
	500	.26	.00	1.85	.65	1.4	.6	.9	.6
	250	.90	.00	2.80	1.30	1.3	.7	1.0	.7
	125	1.21	.03	2.75	1.69	1.3	.9	.8	.7

NOTE: +MA is with S-9 activation, -MA is without such activation.

Table 24. con't.

Sample	Dose µg/plate	Viability Ratio				Mutagenic Ratio			
		TA 98		TA 100		TA 98		TA 100	
		+MA	-MA	+MA	-MA	+MA	-MA	+MA	-MA
XAD Control	1000	.02	.00	.41	.01	.9	.9	.6	.4
	500	.43	.00	2.81	2.11	1.2	.7	.8	.6
	250	.92	.02	2.33	2.41	1.2	1.1	.7	.8
	100	.74	.02	2.71	2.50	1.1	1.0	.8	.6
	10	1.07	.10	2.56	2.28	1.3	1.1	.7	.7

NOTE: +MA is with S-9 activation, -MA is without such activation.

TABLE 25. AMES BIOASSAY RESULTS FOR COAL GASIFIER EFFLUENTS

Coal Type: Wyoming (Smith-Roland) Sub-bituminous

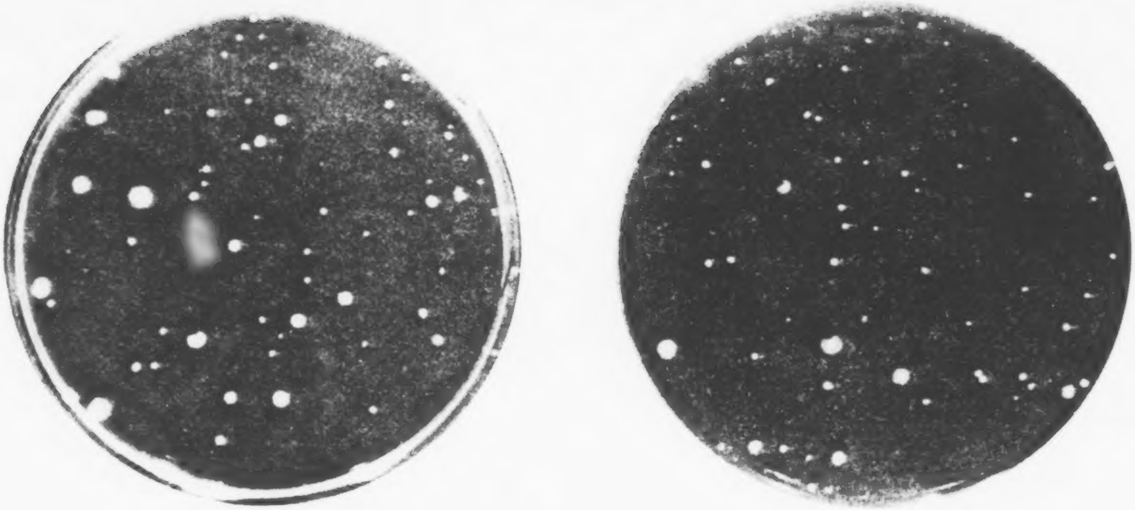
Sample	Dose µg/plate	Viability Ratio				Mutagenic Ratio			
		TA 98		TA 100		TA 98		TA 100	
		+MA	-MA	+MA	-MA	+MA	-MA	+MA	-MA
Crude Tar	1000	.31	.01	.07	.01	6.23	.73	1.19	.60
	500	1.01	.00	1.10	.03	3.15	.73	1.66	.60
	250	1.06	.00	1.36	.17	2.51	.80	1.71	.75
	100	.88	.63	1.27	.69	2.00	.75	1.43	.79
	10	1.06	.02	1.31	1.48	1.67	.95	1.30	.91
Water Condensate	1000	1.08	.88	1.23	.92	1.11	1.02	1.39	1.34
	500	1.34	.75	1.16	.82	1.42	1.03	1.09	.88
	250	1.04	.74	1.04	.85	.99	1.01	1.22	.85
	100	1.30	.86	.93	1.08	1.30	.81	1.00	.90
	10	1.10	.87	.79	.76	1.04	.82	1.07	.92
PNA	1000	.08	.01	.03	.01	17.32	.28	1.09	.61
	500	.61	.08	.40	.04	2.20	.69	1.51	.78
	250	.88	.18	.76	.11	2.88	.81	1.81	.83
	100	.91	.55	1.47	.14	2.15	.35	1.76	.65
	10	.98	.70	1.64	1.33	1.27	.55	1.21	.72
PN	1000	.21	.02	.03	.01	8.88	.27	1.21	1.06
	500	.91	.17	1.56	--	3.31	.39	1.58	.55
	250	.89	.73	1.54	.02	2.35	.37	2.00	.59
	100	.92	1.03	1.64	.36	1.96	.54	1.51	.86
	10	.93	.87	1.54	1.18	1.16	.99	1.13	.89
Acids	1000	.02	.01	.01	.01	.72	0	.57	.00
	500	.85	.01	.46	.01	.91	.17	1.13	.45
	250	1.46	.34	1.08	.02	1.05	.30	1.11	.82
	100	.79	.79	1.12	.41	.99	.64	1.09	.90
	10	.75	.83	.98	.95	.73	.52	1.04	.89

NOTE: +MA is with S-9 activation, -MA is without such activation.

Table 25. con't

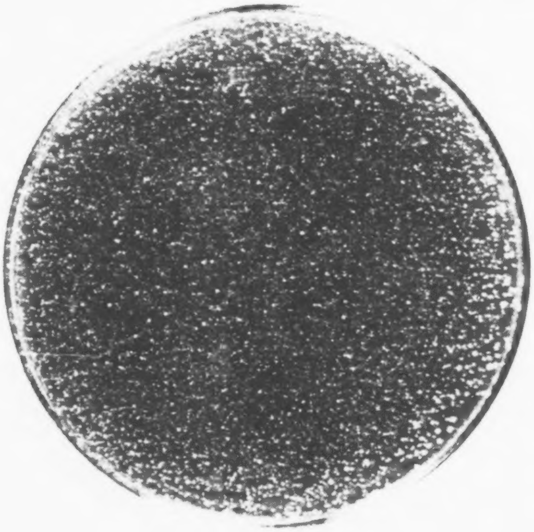
Sample	Dose µg/plate	Viability Ratio				Mutagenic Ratio			
		TA 98		TA 100		TA 98		TA 100	
		+MA	-MA	+MA	-MA	+MA	-MA	+MA	-MA
Bases	1000	.79	.92	1.04	.60	12.31	.70	3.29	1.19
	500	.87	.80	1.28	1.08	6.95	.67	3.00	1.21
	250	.84	.73	1.17	1.03	3.73	.54	2.11	1.11
	100	.85	.56	1.26	.97	1.59	.62	1.61	1.02
	10	1.15	.75	1.02	.98	1.06	.61	1.31	.79

NOTE: +MA is with S-9 activation, -MA is without such activation.



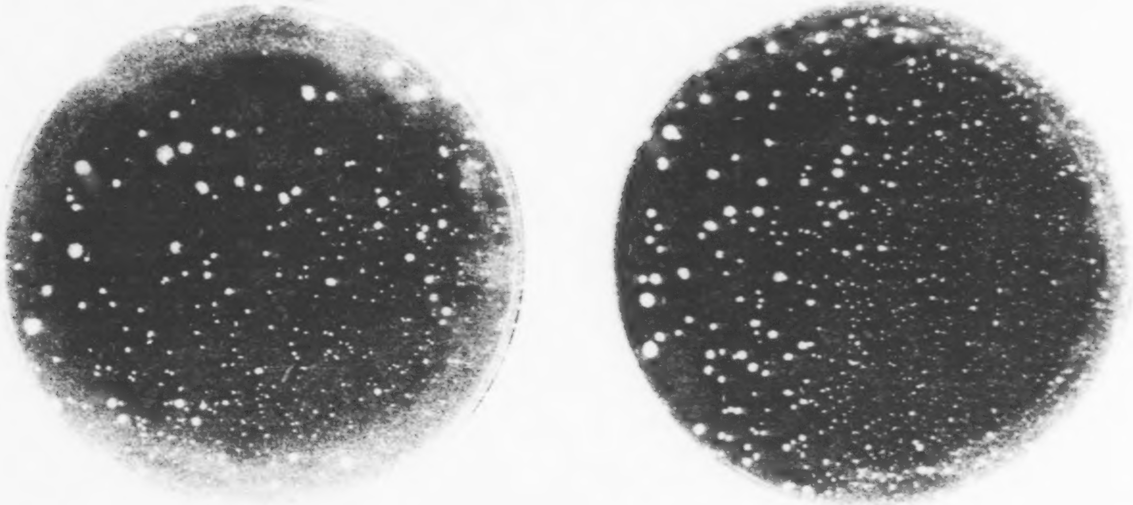
DMSO 100 µl/plate
S-9 3.0 mg protein/plate

Acid 100 µg/plate
S-9 3.0 mg protein/plate
Negative mutagenicity test
Wyoming, 80725, run 35



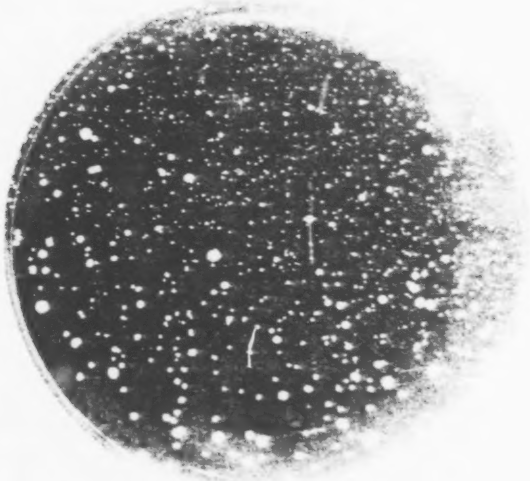
2 Aminoanthracene 100 µg/plate
S-9 3.0 mg protein/plate

Figure 6. Ames bioassay plates (Salmonella strain TA-98).



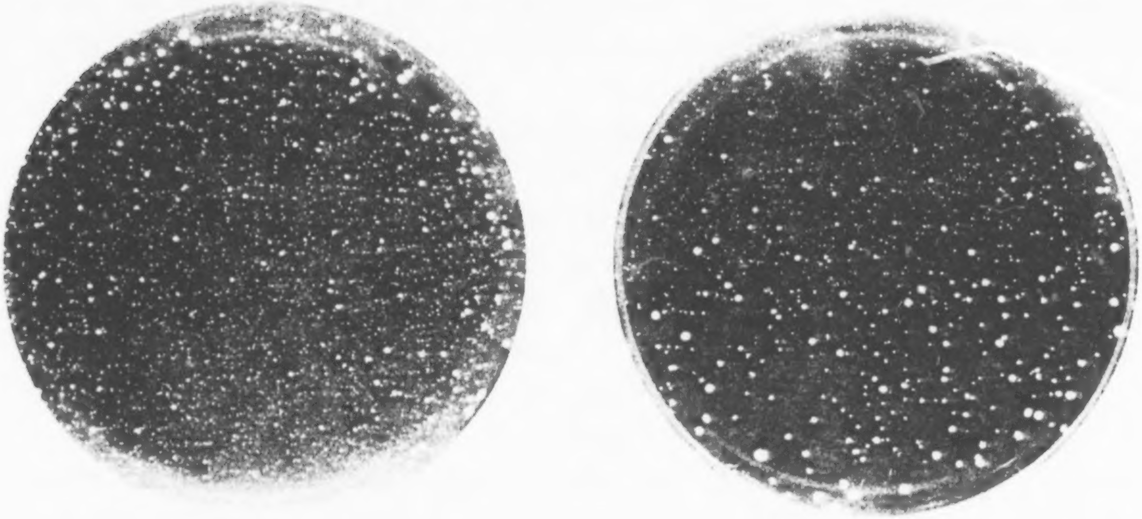
PNA 250 µg/plate
S-9 1.5 mg protein/plate

PNA 500 µg/plate
S-9 3.0 mg protein/plate



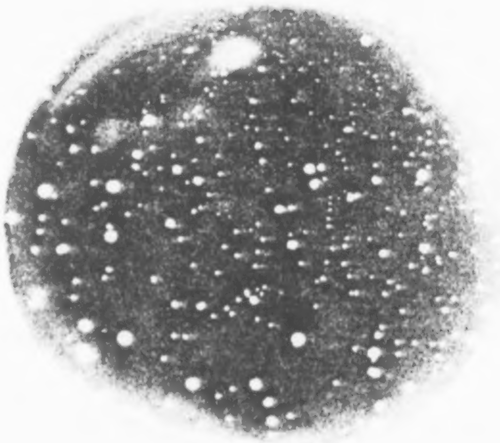
PNA 500 µg/plate
S-9 6.0 mg protein/plate

Figure 7. Ames bioassay plates (PNA fraction from Illinois No.6 coal gasifier tar).



Base 125 µg/plate
S-9 3.0 mg protein/plate

Base 62.5 µg/plate
S-9 3.0 mg protein/plate



Base 25 µg/plate
S-9 3.0 mg protein/plate

Figure 8. Ames bioassay plates (base-fraction from Wyoming subbituminous coal gasifier tar).

plates contained 25, 62.5, and 125 μg of organic tar base fraction per plate. The number of revertant colonies per plate is clearly seen to increase with dose of sample.

The overall results from the Ames bioassays on gasifier tars and tar fractions are presented in the Table 26. This table contains results for raw crude tars as well as the tar base, tar acid, PNA, polar neutral, and nonpolar neutral partition fractions. These represent samples obtained from the RTI laboratory gasifier using North Dakota lignite, Wyoming subbituminous coal, Western Kentucky No.9 coal, and Illinois No.6 coal.

Substantial potential mutagenicity was detected in the crude tar samples. As can be seen in the table, the number of revertants/μg was 11 for the Illinois No.6 coal, 8.7 for the Western Kentucky No.9 coal, and of the order of 2 or less for the other crude tar samples. The highest specific activity of any sample was obtained for the polar neutral fraction of crude tar obtained from Illinois No.6 coal. This sample gave rise to 37.5 revertants/μg. The other samples showing high activity were the base fractions from Western Kentucky No.9 coal which gave rise to 33.8 revertants/μg, the tar base fractions from North Dakota lignite giving 18 revertants/μg and the tar base fraction from Run 35 which utilized Wyoming subbituminous coal giving 15.6 revertants/μg. Thus, it can be seen that while the largest single response was achieved for the polar neutral fraction of Illinois No.6 coal, the primary activity was possessed by tar base fractions from Western Kentucky, Wyoming subbituminous coals, and North Dakota lignite.

5.3 EFFLUENT BIOASSAYS (CHO)

The results of cytotoxicity studies on coal gasifier tars and tar fractions as obtained using Chinese hamster ovary cells in culture are presented in Table 27. Here it is shown that crude tar samples, partitions of the crude tars obtained via solvent partitioning as described earlier in this report, XAD-2 resin samples and aqueous condensates were tested in both the growth kinetics and clonal efficiency assays. At low concentrations, the aqueous condensate sample showed a negligible influence on CHO cells. At higher concentrations, inhibition in the clonal efficiency test was determined at a sample concentration of 125 mg/ml. Further, the XAD-2 control sample was found to exhibit some cytotoxicity in the clonal efficiency assay but none in the growth kinetics test. The surge and steady-state XAD-2 resins exhibited

TABLE 26. AMES BIOASSAY RESULTS FOR GASIFIER TARS AND TAR FRACTIONS

Fraction	Percent of Crude Tar	Dose Rendering a Mutagenic Response (μg)	Specific Activity[1] (revertants/μg)	Activity[2] (revertants)
Run No. 51 (North Dakota Lignite)				
Raw Crude Tar	100.0	250,100	1.915	191.5
Tar Base	4.6	100,10	17.91	81.5
Tar PNA	36.3	500,250,100,10	0.852	30.9
Tar Polar Neutral	7.8	500,250,100,10	1.91	14.8
*Tar Acid	23.6	-	-	-
*Tar Nonpolar Neutral	17.1	-	-	-
				127.2[+]
Run No. 33 (Wyoming Subbituminous Coal)				
Raw Crude Tar	100.0	250,100	1.189	118.9
Tar Base	3.3	250,125,62.5	8.50	23.6
Tar PNA	40.0	1000,500,250,100	1.56	62.3
Tar Polar Neutral	7.5	250,125,62.5	1.42	10.6
*Tar Acid	26.7	-	-	-
*Tar Nonpolar Neutral	20.8	-	-	-
				101.2[+]
Run No. 35 (Wyoming Subbituminous Coal)				
Raw Crude Tar	100.0	500,250,100	0.399	39.9
Tar Base	3.4	125,62.5,25	15.62	53.7
Tar PNA	35.4	500,250,100	0.652	23.1
*Tar Polar Neutral	0.3	-	-	-
*Tar Acid	29.6	-	-	-
*Tar Nonpolar Neutral	18.2	-	-	-
				76.8[+]
Run No. 47 (Wyoming Subbituminous Coal)				
Raw Crude Tar	100.0	500,250,100	0.265	26.5
Tar Base	2.5	100,50,25	5.8	14.7
Tar PNA	36.3	500,250,100	0.36	12.7
Tar Polar Neutral	7.8	500,250,100	0.30	2.3
*Tar Acid	30.7	-	-	-
*Tar Nonpolar Neutral	27.8	-	-	-
				29.8[+]
Run No. 41 (Western Kentucky No.9 Coal)				
Raw Crude Tar	100.0	500,350,100,10	8.69	869
Tar Base	7.0	100,10,1	33.79	235.9
Tar PNA	61.8	250,100,10	7.72	477.0
Tar Polar Neutral	5.3	250,100	1.77	9.4
*Tar Acid	5.3	-	-	-
*Tar Nonpolar Neutral	12.6	-	-	-
				722.3[+]
Run No. 44 (Illinois No. 6 Coal)				
Raw Crude Tar	100.0	250,100,10	11.29	1129
Tar Base	6.7	250,100	6.23	47.0
Tar PNA	66.7	500,250,100	1.96	131.1
Tar Polar Neutral	3.6	50,25,10	37.46	136.0
*Tar Acid	6.7	-	-	-
*Tar Nonpolar Neutral	11.3	-	-	-
				314.1[+]

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[1] Specific Activity = (revertants with sample - spontaneous revertants)/dose.

[2] Activity = specific activity x fraction mass per 100 μg of composite material (corrected for toxicity).

*Nonmutagenic.

[+] Sum of mutagenic activity for fractions comprising the crude tar.

TABLE 27. CYTOTOXICITY OF COAL GASIFIER TARS AND FRACTIONS TO CHINESE HAMSTER OVARY CELLS IN CULTURE

	Sample	% Total Crude Tar	Concentration mg/ml	mg Sample Per 2 ml	Growth Kinetics % Inhibition	Clonal Efficiency % Inhibition
Western Kentucky	Crude Tar	100.00	10.0	250	83	56
				100	69	45
	PNA	61.79	10.0	250	69	23
				100	43	12
	Polar neutrals	5.32	10.0	250	0	0
				100	5	12
	Acids	5.32	5.0	125	69	12
				50	52	0
	Bases	6.98	15.0	375	90	53
				150	74	50
	Non-polar neutrals	12.62	10.0	250	96	23
				100	90	5
	Cyclohexane Insolubles	7.97	10.0	250	22	20
				100	22	17
	XAD-2 Steady State	-	5.0	125	79	35
				50	63	38
	XAD-2 Surge	-	5.0	125	22	30
				50	22	9
	XAD-2 Control	-	5.0	125	0	26
				50	0	6
	H_2O Condensate	-	10.0	250	0	45
				100	0	0
Wyoming	Crude Tar	100.0	5.0	125	36	26
				50	36	5
	PNA	36.26	10.0	250	94	80
				100	63	40
	Polar neutrals	7.76	1.0	25	78	38
				10	64	56
	Acids	30.7	1.0	25	83	54
				10	71	49
	Bases	2.54	0.1	2.5	6	12
				1.0	28	10
	H_2O Condensate	-	Concentrate	28	45	19
					0	0
Illinois #6	Crude Tar	100.00	10.0	250	72	100
				100	72	98
	PNA	66.67	10.0	250	77	95
				100	60	70
	Acids	6.67	5.0	125	0	15
				50	0	18
	Bases	6.67	0.1	2.5	0	12
				1.0	0	22
	Polar neutrals	3.63	2.5	62.5	0	42
				25	0	50
	Non-polar neutrals	11.25	10.0	250	72	88
				100	44	98

some inhibition in both CHO tests with the steady-state sample showing a somewhat more significant response.

The highest responses in the CHO growth kinetics assay resulted from both crude tars and their partition fractions, including the organic bases, PNAs, polar neutrals, and in some cases, the organic acid fractions. Similar results were obtained for the clonal efficiency assay.

The crude tar samples from Illinois No.6 and Western Kentucky No.9 coal gasification runs were found to possess the same level of cytotoxicity per unit mass as was exhibited by the combination of their partition fractions. However, the crude tar sample from the Wyoming subbituminous gasification run was substantially less cytotoxic per unit mass than its partition fraction equivalent. For the Illinois No.6 coal, the nonpolar neutral and PNA fractions exhibited high cytotoxicity; for the Western Kentucky No.9 coal, the organic bases, organic acids, and PNAs were found to be most cytotoxic; while for the Wyoming subbituminous coal, the PNAs organic acids and polar neutrals exhibited greatest cytotoxicity.

6.0 DISCUSSION OF RESULTS

Generally, the results which have been generated in this project on the environmental evaluation of coal gasification screening tests are of four types. First, concentration values for a wide variety of chemical compounds and species have been generated for not only the gasifier gaseous stream but the aqueous condensate, gasifier tar, and reactor residue (ash). Next, production factors have been computed which express the mass of potential pollutant generated in the laboratory gasifier per unit mass of coal converted in the reactor. Then, based upon the MEG methodology, discharge severity values have been computed base upon both DMEG (health) and DMEG (ecology) values. Finally, bioassay results have been obtained for a variety of samples using the Ames, CHO growth kinetics, and CHO clonal efficiency assays.

6.1 CHEMICAL ANALYSIS RESULTS

A compilation of experimentally measured concentrations for the various species determined in the RTI laboratory gasifier product gas stream, aqueous condensate stream, gasifier tar stream, and reactor residue (ash) stream have been provided in the Appendix. These concentration values have been expressed in standard units of measurement to facilitate the environmental analyses of these data. As can be seen in Tables I-1 through I-4 a wide variety of compounds were quantitatively analyzed. The chemical species which occurred in highest concentrations in the gas stream were carbon dioxide, carbon monoxide, methane, and hydrogen. (Nitrogen was also present as diluent in the stream as a result of the nitrogen component of the air which was fed to the gasifier.) Additional chemical species which represent potential pollutants include hydrogen sulfide, benzene, thiophene, toluene, and ethane in this stream. A substantial number of other compounds were also determined as can be seen in these tables.

The organic species present in the aqueous condensate were primarily phenol, cresols, xylenols, and related compounds. In addition, naphthalene and its derivatives plus chrysene, phenanthrene, acenaphthylene and flourene were the predominant organic species present. The inorganic species which predominated in the aqueous condensate stream were ammonia, cyanide, and thiocyanate.

The gasifier tar stream contained significant quantities of xylenols, cresols, and related phenolic compounds. Additionally, the tar was composed of naphthalene, benzofluorene, pyrene, phenanthrene, anthracene, and a large number of higher molecular weight polycyclic aromatic hydrocarbons. Additionally, substantial quantities of heterocyclic oxygen, nitrogen, and sulfur species were present. Chromium, arsenic, lead, and selenium were the predominant elemental species of the reactor residue of environmental concern. The concentrations in μg/g of residue for these species are presented for selected run ash samples in Table I-4. The chromium content of the various gasifier effluent streams must be regarded primarily as an artifact of the particular laboratory configuration used in these studies. This is a consequence of the fact that the stainless steel reactor utilized in these studies possessed a high chromium level from which significant contributions to the effluents took place.

The production factors for selected chemical species from the RTI semibatch laboratory reactor tests have been compiled in Table 28. Here it is seen that on a unit mass of carbon converted basis that hydrogen sulfide, thiophene, phenolic species, benzene, toluene, and naphthalene were predominant. These chemical constituents were found to be present in the various gasification test runs without regard to the particular coal being gasified. While some variation in these production factors was found from one coal to the next, it was generally true that the primary potential pollutants generated in the laboratory gasifier can be taken to be effectively the same under the conditions of these studies without regard to coal type.

The maximum production values for consent decree pollutants in various screening tests have been compiled in Table 29. Of the organic species, it was found that benzene and toluene are predominant of the order of 10,000 g/metric ton of coal loaded to the reactor. A number of other significant organic species were phenol, naphthalene, fluoranthene, and higher molecular weight aromatic species. Ammonia was the most predominant inorganic species which gave rise to a production factor of 5,000 g/metric ton of coal used. Again, the chromium value in this table must be discounted due to the contribution of chromium from the stainless steel reactor used in these studies.

TABLE 28. SELECTED POLLUTANT PRODUCTION IN A LABORATORY COAL GASIFICATION SYSTEM
(μg compound produced/g carbon converted)[a]

Compound	Illinois No.6 Bituminous	Montana Rosebud	Wyoming Subbituminous	North Dakota Lignite	Western Kentucky No.9 Bituminous
hydrogen sulfide	3.8E3	4.6E3	3.4E3	4.9E2	4.0E4
carbonyl sulfide	4.0E2[b]	1.5E2	2.0E2	3.7E2	8.5E2
thiophene	1.8E3	5.2E1	1.6E1	1.1E3	4.0E2
methylthiophene	3.2E2	1.1E1	1.8E2	2.9E1	4.9E2
hydrogen cyanide	NA[c]	1.2E2	NA	1.4E2	NA
ammonia	NA	8.7E3	NA	6.0E3	NA
phenol	4.3E2	1.3E0	NA	1.4E3	1.2E3
cresols	7.2E2	8.3E2	2.7E3	1.0E3	1.3E3
xylenols	NA	1.0E3	8.9E2	1.1E3	2.9E2
benzene	5.0E3	1.9E2	3.1E3	1.1E4	1.9E4
toluene	3.5E4	1.0E3	3.3E3	3.1E3	3.0E3
xylenes	8.9E1	8.9E2	8.1E2	8.3E2	4.1E2
naphthalene	1.2E3	5.9E2	6.3E2	5.2E2	3.5E3
anthracene	7.1E2	2.0E2	1.5E2	2.1E2	1.0E3
phenanthrene	2.2E2	5.9E2	7.2E1	1.3E2	9.8E2

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[a] Results are expressed as "aEb" which should be interpreted as $a \times 10^{b}$.

[b] Includes sulfur dioxide.

[c] NA = Not Available.

TABLE 29. MAXIMUM PRODUCTION OF CONSENT DECREE POLLUTANTS IN SCREENING TESTS

	Exit Gas Concentration (μg/m^3)**	Production Factors g/metric ton
Acenaphthene	4.6E4 (9)	1.2E2
Acenaphthylene	1.5E5 (3)	3.8E2
Anthracene*	1.8E5 (11)	6.7E2
Benzene	3.4E6 (12)	1.3E4
Benzo(a)anthracene*	5.8E4 (3)	1.5E2
Benzo(g,h,i)perylene	2.3E4 (3)	5.9E1
Benzo(a)pyrene*	4.6E4 (3)	1.2E2
Chrysene*	7.9E4 (11)	2.8E2
Dibenzo(a,h)anthracene*	3.6E4 (3)	9.2E1
Ethylbenzene	1.1E5 (8)	4.2E2
Fluoranthene*	2.6E5 (13)	1.0E3
Fluorene	6.0E4 (13)	2.3E2
Naphthalene*	8.4E5 (13)	3.0E3
Phenol*	7.4E5 (12)	1.6E3
Pyrene	1.9E5 (13)	7.4E2
Toluene*	7.5E6 (12)	2.0E4
Ammonia*	2.1E6 (2)	5.0E3
Antimony	4.5E0 (7)	1.5E-2
Arsenic*	2.2E2 (8)	7.7E-1
Cadmium*	3.0E1 (8)	1.0E-1
Chromium*	1.1E3 (7)	2.7E0
Lead*	5.5E2 (7)	1.2E-1

*Concentration exceeds DMEG value.

**Concentrations on moisture-free basis.

( )Number of gasifier runs examined.

This table shows some 14 chemical compounds or species which exceed the corresponding DMEG (health) values. The additional results obtained from the MEG methodology analysis are presented in the next section.

6.2 MEG METHODOLOGY RESULTS

The results of the MEG environmental assessment of screening test results were presented in Section 4 of this report. The results of this analysis are summarized in Table 30 which presents severity rankings for the potential pollutants of the RTI coal gasification effluent streams. Distinct listings are presented for the gas, aqueous condensate, tar, and reactor residue. These results were obtained utilizing the concentration values presented in the Appendix to this report and the appropriate DMEG (health) values for each of the compounds in question. The values in parentheses in this table represent the order of magnitude of the discharge severity determined using health-based data. As can be seen in this table, the predominant species in terms of discharge severity were found in the tar stream to be perylene, benzo(a)pyrene, phenolic species, and a number of other compounds. Cresols, xylenols, and related phenolic compounds were found at high levels in the aqueous condensate stream. Some representation of polycyclic organic species in the aqueous condensate stream was also found.

In the gas stream, the discharge severity ranking gave rise to carbon monoxide as the predominant species while benzene, pyrene, hydrogen sulfide, and other compounds were also present at reasonably high levels. Arsenic and selenium were the two species of the reactor residue which appeared to have potential health hazard significance.

A summary of the data on compounds which have been identified in various coal gasification processes as a part of the EPA environmental assessment program which possess potential for health hazard effects have been tabulated in Tables 31 through 35. These tables represent data for the RTI laboratory gasifier,[2] the Kosovo Lurgi-type gasification plant of Yugoslavia,[20] various Lurgi results as available in the literature,[23] the Wellman-Galusha gasifier of the Glen Gery facility in utilizing Pennsylvania anthracite coal,[24] and the Chapman gasifier utilizing Virginia bituminous coal.[25] In Table 35, the

TABLE 30. SEVERITY RANKING OF POLLUTANTS IN COAL GASIFICATION SCREENING TEST EFFLUENTS RUNS

Tar Stream	Gas Stream	Aqueous Condensate Stream
perylene (10^8)	carbon monoxide (10^4)	cresols (10^5)
benzo(a)pyrene (10^7)	benzene (10^3)	xylenols (10^5)
cresols (10^7)	$C_{16}H_{10}$: 4 rings (10^3)	(chromium (10^4))
xylenols (10^7)	hydrogen sulfide (10^3)	ammonia (10^3)
triphenylene (10^6)	hydrogen (10^2)	trimethylphenol (10^3)
dibenzo(a,h)anthracene (10^6)	carbon dioxide (10^2)	benzo(a)pyrene (10^2)
trimethylphenol (10^6)	xylenols (10^2)	perylene (10^2)
o-isopropylphenol (10^6)	carbonyl sulfide (10^2)	phenol (10^2)
(chromium (10^5))	thiophene (10^2)	arsenic (10^2)
arsenic (10^4)	methanethiol (10)	triphenylene (10)
benz(a)anthracene (10^3)	ethanethiol (10)	cyanide (10)
acenaphtylene (10^3)	carbon disulfide (10)	thiocyanate (10)
phenanthrene (10^3)	sulfur dioxide (10)	cadmium (10)
9-methylanthracene (10^3)	phenol (10)	lead (10)
benzo(g,h,i)perylene (10^3)	C_2-phenol (10)	
chrysene (10^3)	cresols (10)	
phenol (10^3)	ammonia (10)	Solid Residue (Ash)
acenaphthene (10^2)	hydrogen (sulfide (10)	(chromium (10^4))
benzo(b)fluoranthene (10^2)	naphthalene (10)	arsenic (10^2)
indeno(1,2,3-cd)pyrene (10^2)	indene (10)	selenium (10)
quinoline (10^2)		
benzidine (10^2)		
sulfur (10^2)		
anthracene (10)		
fluorene (10)		
fluoranthene (1)		
pyrene (10)		
benzo(e)pyrene (10)		
benzo(a)fluorene (10)		
benzo(k)fluoranthene (10)		
benzothiophene (10)		
carbazole		
cadmium (10)		
lead (10)		

( ) - Order of magnitude of Dischatge Severity (health).

TABLE 31. SUBSTANCES HAVING ENVIRONMENTAL IMPACT POTENTIAL IDENTIFIED IN RTI LABORATORY GASIFIER EFFLUENT STREAMS (Various Coals)

Raw Product Gas	Aqueous Condensate	Tar	Ash
Methane	Phenol	Biphenyl	Arsenic
Methanethiol	Cresols	Phenol	Beryllium
Ethanethiol	Xylenols	Cresols	Chromium
Benzene	Ammonia	Xylenols	Iron
Toluene	Hydrogen Sulfide	Naphthylene	Manganese
Xylenes	Hydrogen Cyanide	Anthracene	Nickel
Indene	Benzo(a)pyrene	Phenanthrene	Selenium
Biphenyl	Naphthalene*	Quinolines	Sodium
Phenol	Monoalkylnaphthalenes*	o-isopropylphenol	Aluminum*
Cresols	Acenaphthylene*	Trimethylphenol	Antimony*
Xylenols	Phenanthrene*	1-Methylnaphthalene	Cadmium*
Naphthalene	Anthracene*	2-Methylnaphthalene	Cerium*
Phenanthrene	Fluoranthene*	C_2-Naphthalenes	Chlorine*
Quinolines	Benzo(b)fluoranthene*	Pyrene	Cobalt*
Thiophene	Benzo(h)fluoranthene*	Benz(a)anthracene	Copper*
Methylthiophene	Benzo(e)pyrene*	Chrysene	Lanthanum*
Carbon Monoxide		Benzo(e)pyrene	Lead*
Carbon Dioxide		Benzo(a)pyrene	Magnesium*
Ammonia		Dibenz(a,h)anthracene	Mercury*
Hydrogen Sulfide		Fluoranthene	Rubidium*
Ethylbenzene*		Benzo(b)fluoranthene	Samarium*
Indan*		Benzo(k)fluoranthene	Scandium*
Anthracene*		Indeno(1,2,3-cd)pyrene	Thorium*
Carbonyl Sulfide*		Acridine	Titanium*
Carbon Disulfide*		Carbazole	Uranium*
		Benzothiophene	Vanadium*
		Benzidine*	Zinc*
		Indole*	

*Substances which were also detected and are typically present in such samples, but were below the corresponding DMEG (health) value.

Source: "Pollutants from Synthetic Fuels Production," Research Triangle Institute, U. S. Environmental Protection Agency Grant Project, August 1979.

TABLE 32. SUBSTANCES HAVING ENVIRONMENTAL IMPACT POTENTIAL IDENTIFIED IN KOSOVO EFFLUENT STREAMS (Yugoslavian Lignite)

Lock Hopper Vent Gas	Rectisol Inlet Gas	Phenosolvan Effluent Water	Generator Wastewater
Methane	Methane	Phenolics	Cyanide*
Carbon Monoxide	Carbon Monoxide	Cyanide*	Chloride*
Carbon Dioxide	Carbon Dioxide	Chloride*	
Benzene	Benzene		
Hydrogen Sulfide	Hydrogen Sulfide		
Carbonyl Sulfide	Methanethiol		
Methanethiol	Ethanethiol		
Ethanethiol	Hydrogen Cyanide		
Ammonia	Carbonyl Sulfide*		
Hydrogen Cyanide	Ammonia*		

*Substances which were also detected and are typically present in such samples, but were below the corresponding DMEG (health) value.

NOTE: Analyses were unavailable for other streams for comparison with other gasification plants.

Source: Kosovo Gasification Test Program Results--Part II: Data Analysis and Interpretation, K. J. Bombaugh, et al,; Sym. Env. Aspects of Fuel Conv. Tech., U. S. Environmental Protection Agency, ORD/IERL, Hollywood, FL, April 1979.

TABLE 33. SUBSTANCES HAVING ENVIRONMENTAL IMPACT POTENTIAL IDENTIFIED OR EXPECTED IN LURGI GASIFICATION EFFLUENT STREAMS
(Various Coals: Lignite to Bituminous)

Product Gas	Tar	Oil	Gas Liquor	Ash
Carbon Dioxide	Lithium	Benzene	Phenol	Lithium
Carbon Monoxide	Beryllium	Toluene	Cresols	Beryllium
Methane	Magnesium	Xylenes	Xylenols	Magnesium
Hydrogen Sulfide	Calcium	Styrene	Catechols	Calcium
Ammonia	Strontium	Indan	Resourcinols	Strontium
Mercaptans	Barium	1,2-Benzofuran	Lithium	Barium
Thiophenes	Boron	Indene	Beryllium	Aluminum
Carbonyl Sulfide*	Aluminum	Naphthalene	Selenium	Carbon
Carbon Disulfide*	Silicon	Thiophenes	Fluoride	Silicon
Hydrogen Cyanide*	Lead	Arsenic	Chromium	Lead
	Phosphorus	Barium	Nickel	Phosphorus
	Arsenic	Beryllium	Mercury	Arsenic
	Selenium	Cobalt	Aluminum*	Zirconium
	Titanium	Chromium	Calcium*	Vanadium
	Vanadium	Mercury	Iron*	Chromium
	Chromium	Lithium	Sodium*	Manganese
	Manganese	Manganese	Silicon*	Iron
	Iron	Nickel	Titanium*	Nickel
	Nickel	Lead	Magnesium*	Sodium*
	Mercury	Selenium	Silver*	Titanium*
	Cerium*	Aluminum	Arsenic*	Chloride*
	Cobalt*	Iron	Boron*	Silver*
	Copper*	Silicon	Barium*	Boron*
	Gallium*	Boron*	Cerium*	Cadmium*
	Germanium*	Copper*	Cobalt*	Cerium*
	Molybdenum*	Molybdenum*	Copper*	Cobalt*
	Rubidium*	Phosphorus*	Molybdenum*	Cesium*
	Antimony*	Rubidium*	Manganese*	Copper*
	Scandium*	Antimony*	Phosphorus*	Fluoride*
	Uranium*	Scandium*	Lead*	Gallium*
	Yttrium*	Strontium*	Rubidium*	Germanium*
	Zinc*	Vanadium*	Antimony*	Mercury*
	Zirconium*	Yttrium*	Scandium*	Molybdenum*
	Sodium*	Zinc*	Strontium*	Rubidium*
		Calcium*	Uranium*	Antimony*
		Sodium*	Vanadium*	Scandium*
		Titanium*	Yttrium*	Selenium*
		Magnesium*	Zinc*	Tellurium*
			Zirconium*	Uranium*
				Tungsten*
				Yttrium*
				Zinc*

*Substances which were also detected and are typically present in such samples, but were below the corresponding DMEG (health) value.

Source: M. Ghassemi, et al., Environmental Assessment Report: Lurgi Coal Gasification Systems for SNG, EPA-600/7-79-120, May 1979.

TABLE 34. SUBSTANCES HAVING ENVIRONMENTAL IMPACT POTENTIAL IDENTIFIED IN WELLMAN-GALUSHA GASIFIER EFFLUENT STREAMS
(Feed Coal: Pennsylvania Anthracite)

Coal Hopper Gas	Ash Sluice Water	Ash	Cyclone Dust
Methane	Barium	Aluminum	Aluminum
Carbon Dioxide	Chromium	Arsenic	Antimony
Carbon Monoxide	Iron	Barium	Arsenic
Iron Carbonyl	Lanthanum	Beryllium	Barium
Hydrogen Sulfide	Lithium	Bismuth	Beryllium
Carbonyl Sulfide*	Benzenethiol*	Cadmium	Cadmium
Carbon Disulfide*	Phenols & Cresols*	Calcium	Calcium
Sulfur Dioxide*	Benzo(e)pyrene*	Chromium	Chromium
	Dibenz(a,h)pyrene*	Cobalt	Cobalt
	Ammonium Ion*	Copper	Copper
	Hydrogen Cyanide*	Hafnium	Fluoride
	Thiocyanate*	Iron	Gallium
	Selenium*	Lead	Hafnium
		Lithium	Iron
		Magnesium	Lead
		Manganese	Lithium
		Nickel	Magnesium
		Selenium	Manganese
		Silicon	Mercury
		Silver	Nickel
		Strontium	Selenium
		Thorium	Silicon
		Titanium	Silver
		Vanadium	Thallium
		Zirconium	Thorium
		Antimony*	Titanium
		Mercury*	Vanadium
			Zinc
			Zirconium
			Naphthalene*
			Phenanthrene*
			Fluorene*
			Antimony*

*Substances which were also detected and are typically present in such samples, but were below the corresponding DMEG (health) value.

Source: W. C. Thomas, et al., Environmental Assessment: Source Test and Evaluation Report--Wellman-Galusha (Glen Gery) Low Btu Gasification, August 1979.

TABLE 35. SUBSTANCES HAVING ENVIRONMENTAL IMPACT POTENTIAL IDENTIFIED IN CHAPMAN GASIFIER EFFLUENT STREAMS
(Virginia Bituminous Coal)

Coal Feeder Vent Gas	Separator Vent Gas	Ash	Separator Liquor	Byproduct Tar
Carbon Dioxide	Carbon Dioxide	Lithium	Ammonia	Carboxylic Acids
Carbon Monoxide	Carbon Monoxide	Rubidium	Cyanide	Amines
Nitrogen Oxide	Nitrogen Dioxide	Beryllium	Thiols	Benzenes
Ammonia	Ammonia	Magnesium	Phenols	Phenols
Cyanide	Cyanide	Calcium	Fused Aromatic Hydrocarbons	Fused Aromatic Hydrocarbons
Hydrogen Sulfide	Hydrogen Sulfide	Strontium	Heterocyclic Nitrogens	Heterocyclic Nitrogens
Carboxylic Acids	Carboxylic Acids	Barium	Heterocyclic Sulfurs	Heterocyclic Oxygens
Amines	Amines	Aluminum	Phosphorus	Heterocyclic Sulfurs
Thiols	Phenols	Silicon	Arsenic	Magnesium
Sulfonic Acids	Fused Aromatic Hydrocarbons	Lead	Selenium	Barium
Benzenes	Heterocyclic Nitrogens	Phosphorus	Fluoride	Lead
Phenols	Heterocyclic Sulfurs	Antimony	Chloride	Antimony
Heterocyclic Nitrogens	Lithium	Selenium	Carboxylic Acids*	Chromium
Heterocyclic Sulfurs	Phosphorus	Fluorine	Lithium*	Copper
Aluminum	Arsenic	Titanium	Rubidium*	Cadmium
Tin	Chromium	Zirconium	Magnesium*	Mercury
Lead	Iron	Vanadium	Calcium*	Rubidium*
Phosphorus	Nickel	Chromium	Barium*	Strontium*
Arsenic	Copper	Iron	Boron*	Boron*
Chromium	Silver	Cobalt	Silicon*	Gallium*
Mercury	Uranium	Copper	Antimony*	Arsenic*
Uranium	Sulfur Dioxide*	Cadmium	Fluorine*	Bismuth*
Nitriles*	Carbonyl Sulfide*	Mercury	Chlorine*	Selenium*
Heterocyclic Oxygens*	Carbon Disulfide*	Uranium	Scandium*	Yttrium*
Lithium*	Heteroyclic Oxygens*	Boron*	Titanium*	Vanadium*
Potassium*	Sodium*	Gallium*	Yttrium*	Niobium*
Magnesium*	Magensium*	Arsenic*	Zirconium*	Lanthanum*
Calcium*	Rubidium*	Yttrium*	Niobium*	Cerium*
Strontium*	Calcium*	Niobium*	Tungsten*	
Barium*	Strontium*	Lanthanum*	Iron*	
Boron*	Barium*	Cerium*	Copper*	
Gallium*	Boron*		Silver*	
Thallium*	Aluminum*		Cadmium*	
Silicon*	Gallium*		Mercury*	
Lead*	Silicon*		Lanthanum*	
Antimony*	Lead*		Cerium*	
Bismuth*	Antimony*		Cesium*	
Sulfur Dioxide*	Selenium*			
Carbonyl Sulfide*	Fluorine*			
Carbon Disulfide*	Fluoride*			
Selenium*	Scandium*			
Fluorine*	Titanium*			
Fluoride*	Zirconium*			
Chloride*	Vanadium*			
Scandium*	Molybdenum*			
Yttrium*	Tungsten*			
Titanium*	Manganese*			
Zirconium*	Cobalt*			
Vanadium*	Zinc*			
Niobium*	Cadmium*			
Molybdenum*	Mercury*			
Tungsten*	Lanthanum*			
Manganese*	Cerium*			
Iron*				
Cobalt*				
Nickel*				
Silver*				
Zinc*				
Lanthanum*				
Cerium*				
Thorium*				

*Substances which were also detected and are typically present in such samples, but were below the corresponding DMEG (health) value.

Source: G. C. Page, Environmental Assessment: Source Test and Evaluation Report--Chapman Low Btu Gasification, EPA-600/7-78-202, October 1978.

substances possessing environmental impact potential for the Chapman gasifier utilizing Virginia bituminous coal are presented for five distinct process streams. These are the coal feeder vent gas, separator vent gas, reactor residue (ash), separator liquor, and byproduct tar stream.

6.3 BIOASSAY RESULTS

The Ames bioassay results for gasifier tar samples and tar fractions from three gasification runs using Wyoming subbituminous coal (Runs 33, 35, and 47) are shown in Figure 9. The consistency of the results among the three crude tar samples is clearly seen. It is evident here from the dose-response relationship for the organic base fraction of the tars that this fraction possesses high potential mutagenicity.

The crude tar samples from four distinct coals are shown in Figure 10 to vary markedly in their response in the Ames bioassay. The Illinois No.6 and Western Kentucky No.9 coal-derived tars were highly toxic to the *Salmonella typhimurium*, unlike the tars from the Wyoming subbituminous coal and North Dakota lignite. A similar comparison of the results of the Ames bioassay with the organic base fractions is shown in Figure 11. Here only the sample derived from Western Kentucky No.9 coal was found to be highly toxic to the bacteria. All of these samples gave high mutagenic ratios, as is seen in this figure.

In order to achieve meaningful results for mutagenic response with the assay it is necessary to correct the data to a constant level of cell survival, i.e., remove the toxicity effect. This has been done for the data of this study; an example is shown in Figure 12. The number of revertants per plate shown in this figure are corrected to a 100 percent cell survival basis.

The Ames and CHO assays on raw coal dust were found to indicate no mutagenic potential based on the techniques utilized in this study. Generally, it is recommended that particulate solids which are tested in bioassay studies should be reduced to 5 micron size or less. The samples tested in this study were at 74 micron or less. However, it is believed that based on the techniques employed and the evidence at hand indicating that the particles used in this study were incorporated into the CHO cells that meaningful results were obtained.

The Ames bioassay test results on coal gasification samples are summarized in Table 36. These results are presented based on the methods of Ames, et al., for conducting Ames bioassay tests.[26] the results are expressed in the so-called

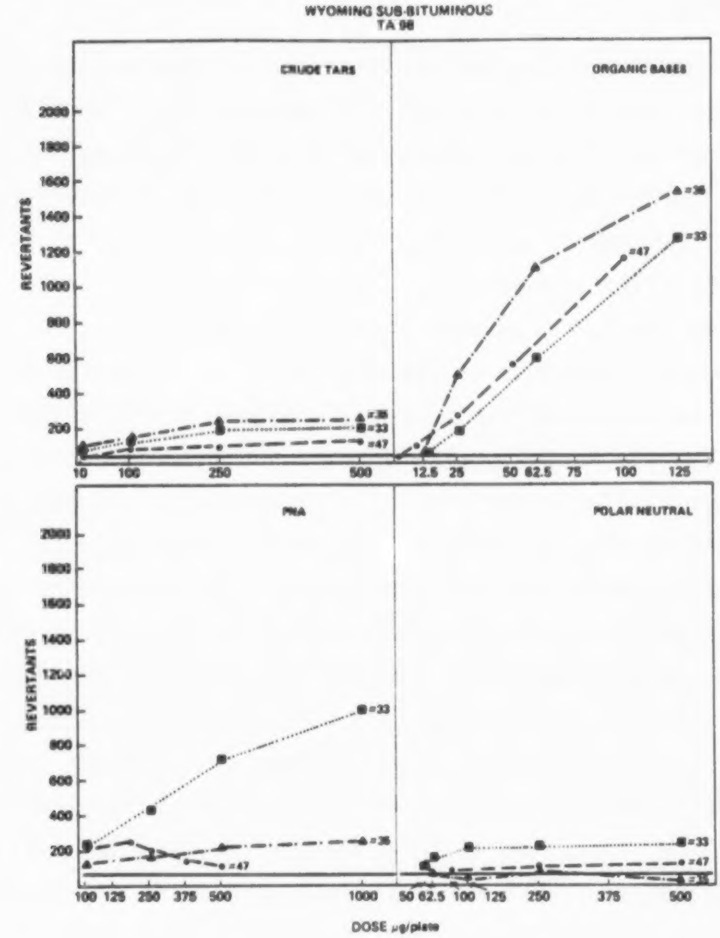

Figure 9. Ames bioassay results for gasifier tar samples and tar fractions from three gasification runs using Wyoming subbituminous coal (Runs No.33, 35, and 47).

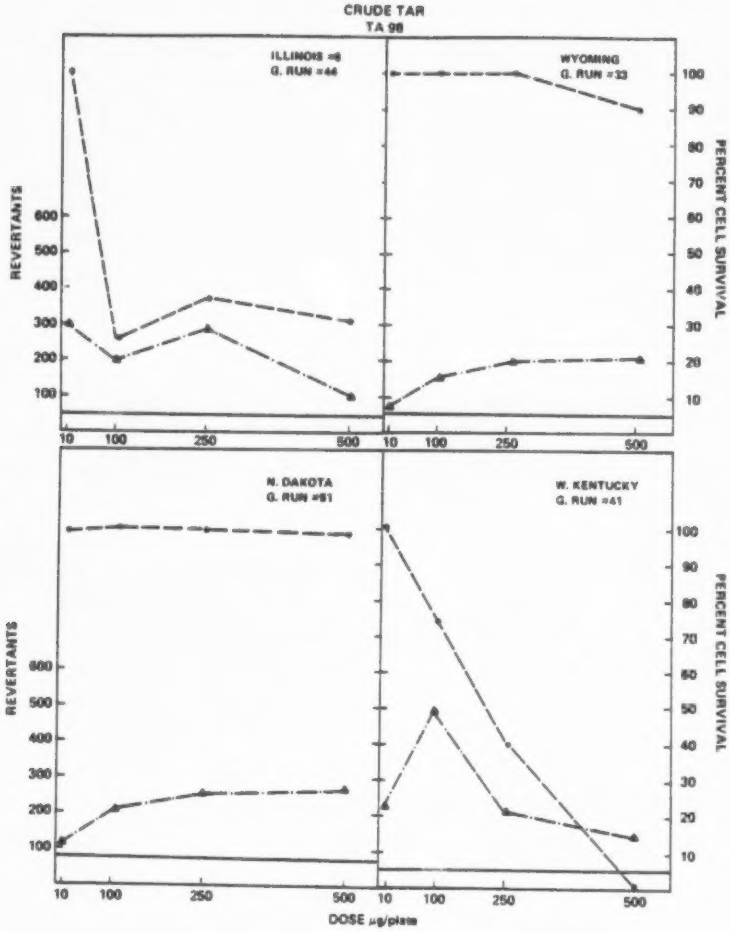

Figure 10. Ames bioassay results for gasifier tar samples from four separate coals (● percent cell survival, ▲ revertants per plate, - control).

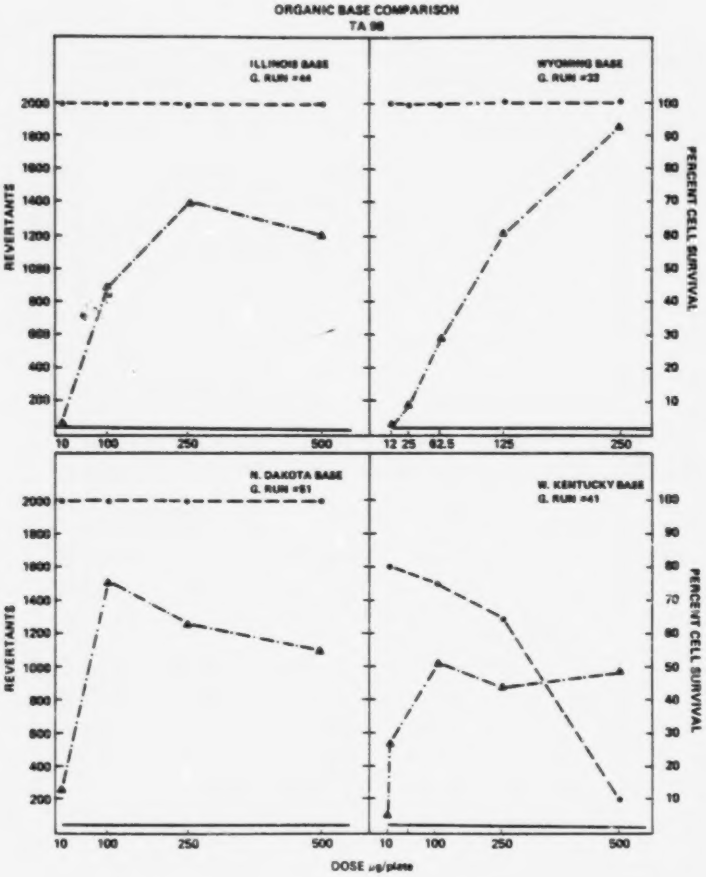

Figure 11. Ames bioassay results for organic base fractions of gasifier tar samples from four separate coals (● percent cell survival, ▲ revertants per plate, - controls).

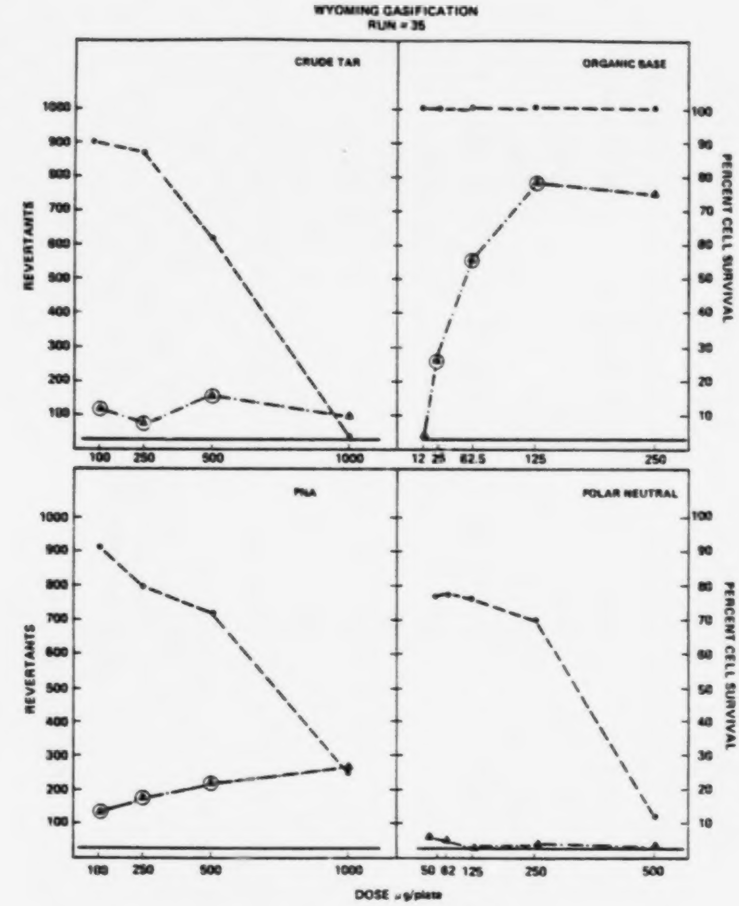

Figure 12. Ames bioassay results for gasifier tar and fractions from Wyoming coal (● percent cell survival, ▲ revertants/plate, ◉ revertants/plate corrected for cell deaths, - control).

TABLE 36. AMES BIOASSAY TEST RESULTS OF COAL GASIFICATION SAMPLES*
(Highest Mutagenic Response Observed in Non-Toxic Dose Range)

SAMPLE/FRACTION	North Dakota Lignite Run #51	Wyoming Subbit. Run #33	Wyoming Subbit. Run #35	Wyoming Subbit. Run #47	W. Kentucky#9 Subbit. Run #41	Illinois#6 Run #44
Crude Tar	M (8.4)	M (3.6)	M (4.6)	M (3.1)	H (19.2)	H (14.6)
Polynuclear Aromatic Hydrocarbon	M (10.0)	M (12.3)	M (5.2)	M (5.7)	H (24.1)	M (31.8)
Polar Neutral	M (7.4)	M (3.8)	Neg.	M (4.7)	M (13.4)	H (28.4)
Nonpolar Neutral	Neg.	Neg.	Neg.	NT	Neg.	Neg.
Organic Acid	Neg.	Neg.	Neg.	Neg.	Neg.	Neg.
Organic Base	H (32.8)	H (31.2)	H (26.3)	H (29.1)	H (42.6)	M (30.0)
Aqueous Condensate	NT	NT	NT	Neg.	Neg.	NT
Hexane Insoluble	NT	NT	NT	NT	Neg.	NT
XAD (surge)	Neg.	NT	NT	NT	Neg.	NT
XAD (steady-state)	Neg.	NT	NT	NT	Neg.	NT

*Brusick Scheme Result (max. revertants/spontaneous revertants):
H - High mutagenicity - mutagenic response occurs at a dose of less than 50 μg.
M - Medium mutagenicity - mutagenic response occurs at a dose of 499 to 50 μg/plate.
L - Low mutagenicity - mutagenic response occurs at a dose of 5000 to 500 μg/plate.
NT - Not tested.
Neg. - Negative Response at the highest concentration tested.

Brusick notation.[27] Here a high mutagenicity is indicated when a sample results in a mutagenicity ratio of 3 or greater at a dose of less than 50 μg. Medium mutagenicity is indicative of a mutagenic ratio of 3 or greater at a dose between 50 to 499 μg/plate. While low mutagenicity is indicative of a mutagenic of 3 or greater obtained at a dose of 500 to 5,000 μg/plate. A negative response would be indicated if higher concentrations were required to elicit a mutagenic ratio of 3 or greater. The viability ratio indicates whether the bacterial cells were capable of surviving the environment created by the test sample. A viability of 50 percent or greater is required before results are given credance. The mutagenicity results which were obtained in this study required metabolic activation (S-9) and were confined to frameshift mutagenesis, i.e., active with strain TA 98 only.

The organic base fraction of the crude tar samples were found to be extremely mutagenic in these studies. This is indicated in Table 36, not only because high mutagenicity ratings resulted via the Brusick scheme for results, but also because the highest mutagenic response observed in the nontoxic dose range was of the order of 30 for these samples. This mutagenicity ratio can be compared with the values of 3 to 19 which resulted for the crude tar samples. The crude tars did show medium to high mutagenicity as can be seen in the table with the Western Kentucky and Illinois coals giving rise to high values; the Wyoming subbituminous and North Dakota lignite samples showed medium mutagenicity. It may also be noted that both the PNA and the polar neutral fraction of the crude tars also gave rise to medium mutagenicity in the case of the Wyoming subbituminous coal and North Dakota lignite samples while somewhat higher mutagenic ratios were obtained for these same samples for the Illinois No.6 and Western Kentucky No.9 derived samples.

It may also be noted that negative results were obtained not only for the aqueous condensate, the XAD-resin cartridges from the surge and steady-state periods of various gasification tests, as well as the nonpolar neutral, organic acid and hexane insoluble partitions of the crude tar samples. It is important to note that the mutagenic ratios obtained for the organic base fractions of the crude samples substantially exceeded the mutagenic ratios of the crude tars themselves. This phenomenon can be referred to as an "unmasking" effect in which the constituents of the organic base fraction and for that matter, the PNA, and in some cases polar neutral fractions, possess substantially higher revertants/μg than the crude tar itself.

Cytotoxicity was studied in this project using Chinese hamster ovary (CHO) cell in culture. The raw coal dusts were noncytotoxic to doses as high as 10/mg dish, although the cells seemed to ingest the dust particles, the cell cytoplasm appearing filled with particles after 24 hours. The CHO cytotoxic activity of the crude tars was similar to their mutagenic activity. Those crude tar extracts which were strongly mutagenic were also typically cytotoxic and some of the tar extracts which were weakly mutagenic were also weekly cytotoxic. Basic organic fractions derived from the tar extracts showed strongly cytotoxic behavior and in this regard, the cytotoxicity results were also similar to the mutagenic results.

Figure 13 provides evidence of the efficacy of the CHO assay for the determination of cytotoxic effects from cadmium. Note that cell survival is a strong function of the cadmium concentration. Generally, it is believed that the Ames test may not be sensitive to inorganic species, particularly as a measure of their potential mutagenicity. Separate assay studies using perhaps CHO cells or other techniques should be useful in this regard.

6.4 OTHER CONSIDERATIONS

Earlier work on the nonisothermal conversion of coals under various operating conditions included the study of a range of coals. Kinetic parameters were measured for a range of gaseous species, including H_2S and acetylene.[32] However, the study was limited due to the sampling and analysis methods employed and the focus on gaseous species to the exclusion of aqueous condensate, tars, and reactor residue, which were examined in this study.

Comprehensive reviews of experimental data on coal conversion processes has been prepared in other related work.[33-35] These provide a useful data base for synthetic fuel production processes. However, the present work is equally comprehensive in terms of its attention to the broad array of chemical constituents present while being more quantitative in nature.

Greenwood, et al.[36] have compiled a handbook (summary) of existing federal regulations and criteria relevant to fossil fuel resource conversion. Yet, as this present study indicates, a number of additional considerations remain to receive attention. Miller[37] discusses the potential problem due to teratogens, carcinogens, and mutagens. Southworth, et al.[38] detail a specific example, which considers the ecological potential of azarenes in freshwater systems.

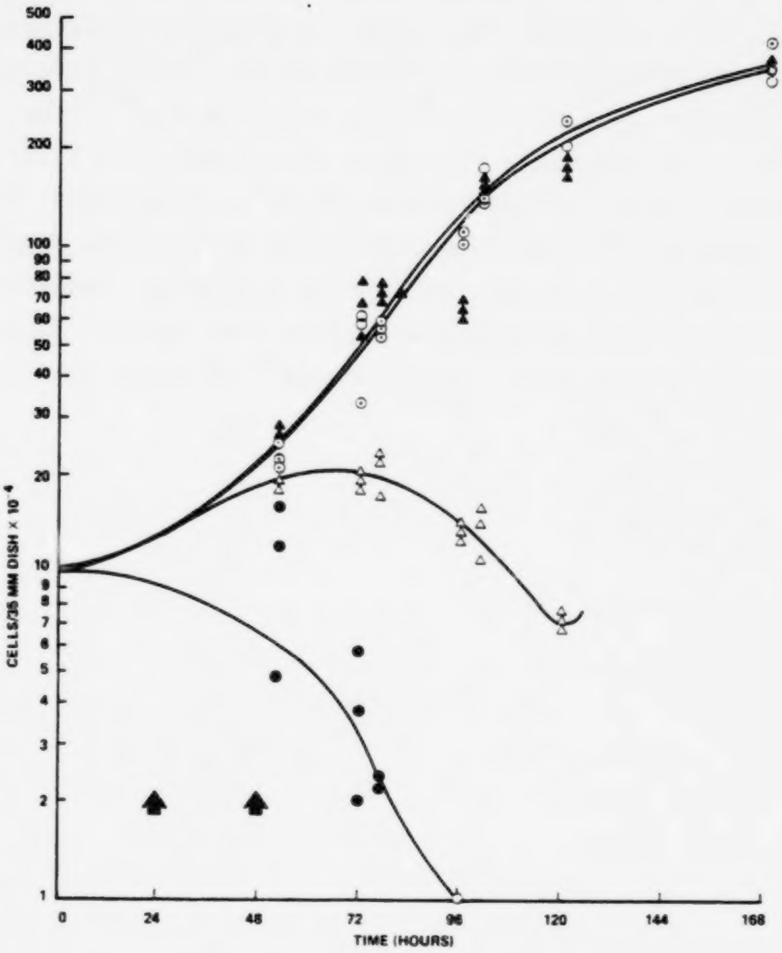

Figure 13. The effect of cadmium on the growth of Chinese hamster ovary cells in culture.

Triplicate cultures of CHO cells are explanted at 10^5 cells, 35 mm dish, incubated 24 hours at 37°C in a 5% CO_2 atmosphere, and $CdCl_2$ at 10^{-8} M (▲), 10^{-7} M (△), and 10^{-6} M (●), was added in 25 μl DMSO, and the cultures incubated 24 hours (arrows), at which time the medium was replaced with fresh medium and incubation continued, counting cells at 24 hour intervals using an automated cell counter. Control cultures were incubated with 25 μl DMSO (○ , ⊙).

Actually, the environmental health problems of synthetic fuel plants must be first regarded from an occupational health and safety perspective. In-plant workers can potentially receive greater exposures than persons in the general geographical area of a synthetic fuel plant. The National Institute of Occupational Health and Safety (NIOSH) has developed some useful information on a few specific compounds including H_2S,[39] coal tar products,[40] cresol,[41] and chyrsene.[42] These and other data on existing Lurgi coal gasification facilities[43-44] provide the basis of preliminary planning of commercial facilities.[45-46]

As pilot, demonstration, and commercial coal gasification facilities are constructed and operated, more data will become available. Environmental monitoring guidelines have been prepared through both the U.S. Department of Energy[47] and the Environmental Protection Agency[48] for these facilities.

7.0 CONCLUSIONS

The objectives of this project have included the construction and operation of a laboratory facility to conduct experimentation on a range of U.S. coals under various operating conditions to determine the potential environmental pollutants which may result therefrom. Thus, it has been sought to determine a fundamental understanding of the nature of the potentail pollutants as well as the importance of those factors which may influence the the production of the various chemical species involved. This information is intended to be used for guidance in the development of control technology and the establishment of guidelines for environmentally safe synthetic fuel plants.

A series of screening test runs has been conducted in the RTI laboratory gasification facility. A variety of coals have been used including Illinois No.6, Western Kentucky No.9, Montana Rosebud, Wyoming subbituminous coals and North Dakota lignite. Chemical analyses of the coal, reactor residue (ash), aqueous condensate, tars and primary gaseous products have been performed. Emphasis has been placed upon determination of these organic constituents in the effluent streams while importance has also been attached to inorganic species in the various streams of the process. The process has involved not only the laboratory gasifier and associated control and data collection system (signal processor) but the development of appropriate sampling, chemical analysis and biological evaluation techniques. Other reports have been prepared on many of these subjects.

Roughly, it has been found that the chemical constituents of the gasifier effluent streams, generated under appropriate conditions of temperature and pressure to result in satisfactory reactor operation at air and steam rates comparable to those of commercial significance, are very much the same without regard to coal type within the range of coals studied in this project. The actual concentration of individual species does in fact depend upon the coal but more significantly, upon the operating conditions of the gasifier and the process configuration relative to filters, traps, condensers, and other process operations.

A variety of chemical constituents have been identified as compounds possessing potential for generating undesirable health effects not only to in-plant workers but to the environment surrounding a synthetic fuels plant. The gas stream has been identified to contain a variety of polynuclear aromatic hydrocarbons, phenolic compounds, and sulfur-containing species in addition to the primary gases of carbon monoxide and hydrogen. The aqueous condensate stream was determined to possess substantial quantities of phenolic compounds, i.e., phenols, cresols, and xylenols, at significant levels from a health and/or ecological perspective. Moreover, the tar stream was also found to contain a variety of phenolic and PNA species at significant concentration levels based on health or ecology-related reference data.

Bioassays on the tar samples indicate that the organic base constituents possess a high potential to create mutagenic changes while the PNA and polar neutral fractions also possess moderate to high rankings. The other fractions of the crude tar as well as the other effluent and related constituents of the gasification process were found to be nonmutagenic. The reactor residue is known to carry trace elements originating in raw coal which have some potential to create severe health effects. These were found to be primarily arsenic and selenium. (Chromium which was found in various of the gasification reactor effluents is known to result primarily from the stainless steel metal from which the gasification reactor was constructed.) It must be noted that to date organometallic compounds have not been identified or quantitated in this study. It is believed, however, that some of the trace element constituents of raw coal may well exist in the gasification process system as a part of organic molecules. These could have potential health effects if released to the environment.

Fugitive emissions are known to be a problem area in the operation of chemical process plants. No systematic approach to the consideration of fugitive emissions has been taken in this study except through analysis and examination of each of the effluent streams from the gasifier. The particular nature and quantity of the various discharges to the environment which would be a part of a commercial coal conversion facility is dependent upon many factors including the environmental control standards prevailing or applicable to that particular facility, the nature of the specific process being employed along with the large number of processing operations to be included in the plant.

Various choices are involved in selecting a gasifier type for a synthetic fuel plant as well as in the development of the process configuration. Not only is it possible to recycle undesirable constituents, i.e., oils, tar, and/or aqueous condensate, to the gasification reactor, but additional process units may be installed to remove and/or contain any of the various species present. However, this study is useful in that it provides a substantial data base for a number of U.S. coals under various operating conditions. While the data were generated in a fixed-bed coal gasification reactor, the data are also of interest in helping to understand other gasification reactor types.

A versatile gasification system for laboratory use has been constructed and operated. This facility has permitted an examination of various coals and operating conditions. The various effluents were analyzed and characterized. Operation of the facility under carefully controlled conditions in which specifically determined variables are set at preselected values can be performed and analyzed. This system gives rise to basic data for an understanding of pollutant formation and their control during coal gasification.

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APPENDIX

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Table I-1: Concentration of Species in Gas Stream I-1

Table I-2: Concentration of Species in Aqueous Condensate I-17

Table I-3: Concentration of Species in Gasifier Tar I-24

Table I-4: Concentration of Species in Solid Residue I-34

TABLE I-1. CONCENTRATION OF SPECIES IN GAS STREAM
(micrograms per cubic meter)

Compound	Methane	Ethane	Propane	n-Butane	Isobutane	Pentanes	Cyclopentane
Mol. Wt.	16	30	44	58	58	72	70
DMEG	3.3E+6	6.2E+6	9.0E+6	1.4E+6	1.4E+6	1.8E+6	3.5E+6
Run No.							
6	5.9E+7	6.5E+6	3.6E+6	2.0E+5	4.0E+5	--	--
16	6.4E+7	1.3E+6	2.9E+5	5.2E+4	5.2E+4	3.2E+4	1.5E+4
20	2.8E+7	9.0E+5	1.4E+5	2.5E+4	2.5E+4	8.0E+3	--
21	3.6E+7	1.3E+6	1.6E+5	6.5E+4	6.5E+4	--	--
23	3.4E+7	--	--	--	--	--	--
25	2.8E+7	--	--	--	--	--	--
26	1.7E+7	--	--	--	--	--	--
31	5.7E+7	--	--	--	--	--	--
32	3.7E+7	--	--	--	--	--	--
33	3.5E+7	--	--	--	--	--	--
35	2.5E+7	--	--	--	--	--	--
36	2.1E+7	--	--	--	--	--	--
38P	2.2E+6	--	--	--	--	--	--
38G	1.6E+7	--	--	--	--	--	--
41	3.5E+7	--	--	--	--	--	--
43	1.7E+7	--	--	--	--	--	--
44	2.1E+7	--	--	--	--	--	--
45	3.0E+7	--	--	--	--	--	--

Table I-1 (continued). GAS STREAM ($\mu g/m^3$)

Compound	3-Methylpentane	Methylcyclopentane	Ethylene	Propylene	1-Butene	2-Pentene
Mol. Wt.	86	84	28	42	56	70
DMEG	3.5E+5	3.5E+5	5.7E+6	8.6E+6	9.1E+6	3.5E+5
Run No.						
6	--	--	--	2.1E+6	--	--
16	6.0E+4	2.3E+4	1.8E+6	3.7E+5	5.6E+4	2.1E+4
20	--	--	2.4E+5	1.0E+5	--	--
21	--	--	9.4E+5	1.9E+5	--	--
23						
25						
26						
31						
32						
33						
35						
36						
38P						
38G						
41						
43						
44						
45						

Table I-1 (continued). GAS STREAM ($\mu g/m^3$)

Compound	2-Methyl-1-Butene	Acetylene	Propyne	Benzaldehyde	Acetophenone	Acetic Acid
Mol. Wt.	70	26	40	106	120	60
DMEG	3.5E+5	2.7E+6	1.7E+6	5.9E+4	4.1E+4	2.5E+4
Run No.						
6	--	--	--	--	--	--
16	1.0E+4	1.2E+4	1.4E+4	2.0E+0	2.7E+4	--
20	--	3.0E+4	--	--	--	--
21	--	1.2E+4	--	--	--	--
23						
25						
26						
31	--	--	--	1.2E+4	--	3.9E+4
32						
33						
35						
36						
38P						
38G						
41						
43						
44						
45						

Table I-1 (continued). GAS STREAM ($\mu g/m^3$)

Compound	Methanethiol	C_2H_6S	Benzene	Toluene	Ethylbenzene	Xylenes	Biphenyl
Mol. Wt.	48	62	78	92	106	106	154
DMEG	1.0E+3	1.0E+3	3.0E+3	3.8E+5	4.4E+5	4.4E+5	1.0E+3
Run No.							
6	4.1E+3	2.5E+4	7.7E+3	5.7E+3	2.2E+4	2.2E+4	4.4E+2
16	8.6E+3	--	1.1E+6	7.8E+6	8.2E+3	2.0E+4	4.0E+2
20	--	--	--	--	--	--	--
21	1.7E+4	--	--	--	8.6E+4	8.8E+4	1.9E+3
23	4.0E+3	4.0E+3	3.0E+6	1.0E+5	8.0E+2	4.0E+3	3.0E+1
25	9.0E+3	3.6E+2	2.5E+6	9.0E+5	8.6E+4	1.1E+5	2.7E+3
26	8.7E+2	--	1.4E+6	2.1E+5	5.8E+4	1.9E+5	6.2E+2
31	1.3E+4	3.0E+3	4.4E+6	6.4E+5	--	--	2.0E+4
32	4.9E+3	--	3.2E+6	1.1E+6	4.9E+4	7.3E+5	1.2E+3
33	6.5E+3	--	2.1E+6	8.4E+5	--	2.1E+5	2.9E+3
35	1.0E+4	--	1.5E+6	8.8E+5	8.0E+4	3.2E+5	1.2E+3
36	3.4E+4	9.7E+3	2.3E+6	6.2E+5	7.6E+4	1.7E+5	1.4E+3
38P	4.5E+3	4.6E+3	1.8E+5	2.7E+5	7.4E+4	2.2E+5	7.8E+2
38G	1.2E+4	5.3E+3	2.8E+5	2.5E+5	2.9E+4	1.6E+5	--
41	1.0E+4	3.0E+4	3.3E+6	4.4E+5	2.1E+4	7.3E+4	1.5E+3
43	5.0E+3	6.0E+3	7.1E+5	4.1E+5	2.7E+4	1.3E+5	9.6E+2
44	1.6E+3	1.4E+4	1.7E+6	4.1E+5	1.5E+4	8.0E+4	5.8E+2
45	6.5E+3	4.4E+3	1.5E+6	8.4E+5	5.7E+4	2.9E+5	--

Table I-1 (continued). GAS STREAM ($\mu g/m^3$)

Compound	Diphenylmethane	C_2H_7-Benzene	C_4-Benzene	C_5-Benzene	Indan	Indene
Mol. Wt.	168	133	137	149	118	116
DMEG	1.0E+3	2.5E+5	2.5E+5	2.5E+5	2.3E+5	4.5E+4
Run No.						
6	--	1.1E+4	4.6E+4	1.5E+4	5.4E+3	8.1E+4
16	--	3.8E+3	2.0E+3	--	1.3E+4	9.1E+4
20	--	--	--	--	--	--
21	3.1E+2	--	--	--	4.9E+3	1.9E+3
23	--	--	--	--	2.0E+2	1.0E+2
25	2.7E+3	--	--	--	5.9E+2	6.3E+4
26	3.1E+2	--	--	--	1.5E+3	3.3E+4
31	3.9E+3	--	--	--	4.1E+4	4.0E+5
32	4.9E+2	--	--	--	2.0E+3	2.4E+4
33	1.3E+3	--	--	--	3.5E+4	2.5E+5
35	6.0E+2	--	2.5E+5	--	7.8E+3	5.6E+4
36	4.7E+2	--	--	--	2.8E+3	3.4E+4
38P	--	--	--	--	2.5E+4	8.6E+4
38G	--	--	--	--	--	--
41	--	--	--	--	1.3E+4	1.3E+5
43	--	--	--	--	7.8E+3	1.0E+5
44	--	--	--	--	2.6E+3	1.0E+5
45	--	--	--	--	--	--

Table I-1 (continued). GAS STREAM ($\mu g/m^3$)

Compound	Xylenes	Diethylbenzene	Trimethylbenzene	Methylindene	C_3-Benzenes
Mol. Wt.	106	134	120	130	120
DMEG	4.4E+5	2.3E+5	1.2E+5	4.5E+4	2.2E+5
Run No.					
6	2.2E+4	--	--	7.1E+4	6.2E+4
16	2.0E+4	2.4E+3	9.6E+2	9.0E+4	2.8E+5
20	--	--	--	--	--
21	8.8E+4	--	--	--	--
23	--	--	--	--	--
25	--	--	--	--	--
26	--	--	--	--	--
31	1.8E+5	--	--	--	--
32	--	--	--	--	--
33	--	--	--	--	1.1E+5
35	--	--	--	--	4.8E+4
36	--	--	--	--	--
38P	--	--	--	--	1.5E+5
38G	--	--	--	--	--
41	1.2E+4	--	--	2.6E+3	3.6E+4
43	3.0E+4	--	--	6.2E+3	4.9E+4
44	6.0E+4	--	--	--	1.1E+4
45	--	--	--	--	--

Table I-1 (continued). GAS STREAM ($\mu g/m^3$)

Compound	Dimethylbiphenyl	Phenol	Cresols	C_2-Phenols	Xylenols	Naphthalene
Mol. Wt.	182	94	108	122	122	128
DMEG	1.0E+3	1.9E+4	2.2E+4	2.5E+4	1.3E+4	5.0E+4
Run No.						
6	--	2.9E+4	1.2E+5	3.8E+5	--	6.2E+4
16	2.0E+3	5.2E+3	4.4E+3	5.0E+3	--	2.8E+4
20	--	--	--	--	--	--
21	--	2.8E+4	6.9E+4	--	6.9E+4	1.7E+5
23	--	--	--	--	--	3.1E+3
25	--	3.9E+4	9.0E+4	--	--	5.9E+5
26	--	3.1E+4	1.1E+4	--	2.2E+4	4.0E+4
31	--	4.3E+5	2.1E+5	--	7.8E+5	2.6E+5
32	--	6.4E+4	3.5E+4	--	6.4E+4	1.4E+5
33	--	5.6E+5	1.5E+5	--	6.5E+5	1.2E+5
35	--	2.4E+5	1.1E+5	--	2.8E+5	3.4E+4
36	--	6.9E+4	5.9E+4	--	2.1E+5	1.0E+5
38P	--	9.1E+4	2.0E+5	--	8.8E+5	4.0E+4
38G	--	--	--	--	--	--
41	--	9.6E+4	6.2E+4	--	--	5.6E+5
43	--	8.3E+3	5.1E+4	--	3.6E+2	2.3E+4
44	--	7.8E+3	1.0E+4	--	--	4.5E+4
45	--	--	--	--	--	--

Table I-1 (continued). GAS STREAM ($\mu g/m^3$)

Compound	α-Methylnaphthalene	β-Methylnaphthalene	Acenaphthene	Anthracene
Mol. Wt.	142	142	154	178
DMEG	2.3E+5	2.2E+5	1.6E+3	2.4E+4
Run No.				
6	1.0E+3	4.4E+2	4.4E+2	7.4E+1
16	2.8E+4	5.0E+3	5.2E+2	5.7E+2
20	--	--	--	--
21	--	--	--	1.6E+3
23	--	--	--	7.0E+0
25	--	--	--	1.2E+3
26	--	--	--	6.2E+2
31	4.0E+4	5.9E+4	8.0E+3	7.6E+3
32	--	--	--	4.0E+2
33	--	--	--	1.1E+3
35	--	--	2.0E+2	4.7E+2
36	--	--	3.0E+2	4.0E+2
38P	--	--	1.3E+2	1.3E+2
38G	--	--	--	--
41	2.4E+3	--	1.3E+3	1.8E+3
43	1.2E+3	2.1E+3	4.0E+0	1.8E+3
44	0.9E+0	0.9E+0	1.0E+0	7.1E+2
45	--	--	--	--

Table I-1 (continued). GAS STREAM (μg/m^3)

Compound	Phenanthrene	Propenylphenanthrene	$C_{15}H_{12}$: 3 Rings	$C_{16}H_{10}$: 4 Rings	Pyrene
Mol. Wt.	178	218	192	202	202
DMEG	1.6E+3	2.4E+4	1.6E+3	2.6E-1	2.3E+5
Run No.					
6	--	--	--	--	--
16	--	7.7E+0	--	--	1.0E+2
20	--	--	--	--	--
21	6.9E+2	--	--	--	--
23	--	--	--	--	--
25	7.8E+2	--	--	--	--
26	--	--	--	--	--
31	2.0E+1	--	--	--	--
32	--	--	--	--	--
33	--	--	--	--	--
35	--	--	8.0E+1	1.7E+2	--
36	--	--	--	--	--
38P	--	--	6.6E+1	2.0E+2	--
38G	--	--	--	--	--
41	--	--	--	--	--
43	6.9E-1	--	2.3E+1	3.8E+1	1.8E+1
44	2.2E+2	--	--	--	--
45	--	--	--	--	--

Table I-1 (continued). GAS STREAM ($\mu g/m^3$)

Compound	Fluorene	Fluoranthene	Pyridine	Benzofuran	Methylbenzofuran
Mol. Wt.	202	166	79	118	132
DMEG	9.0E+2	9.0E+5	1.5E+4	5.3E+6	5.3E+6
Run No.					
6	--	--	--	--	1.0E+4
16	7.0E+0	7.0E+1	--	1.3E+5	4.8E+0
20	--	--	--	--	--
21	--	--		2.1E+4	--
23	--	--	--	5.5E+4	--
25	--	--	--	1.0E+4	--
26	--	--	--	1.3E+5	--
31	3.1E+3	--	--	--	--
32	--	--	--	7.9E+3	--
33	--	--	--	--	--
35	--	--	--	4.2E+4	--
36	--	--	--	6.2E+3	--
38P	--	--	--	1.5E+4	--
38G	--	--	--	--	--
41	--	--	--	3.1E+4	--
43	--	--	--	2.8E+4	--
44	--	--	--	2.2E+4	--
45	--	--	--	--	--

Table I-1 (continued). GAS STREAM ($\mu g/m^3$)

Compound	Dimethylbenzofuran	Dibenzofuran	Thiophene	Methylthiophene	Dimethylthiophene
Mol. Wt.	146	168	84	98	113
DMEG	5.3E+6	5.3E+6	4.5E+3	2.3E+4	2.6E+4
Run No.					
6	1.2E+3	2.0E+3	1.3E+5	4.4E+4	4.4E+4
16	--	--	4.0E+5	1.7E+3	1.7E+3
20	--	--	--	--	--
21	--	9.8E+3	1.2E+5	--	--
23	--	--	--	--	--
25	--	1.2E+4	6.6E+5	--	--
26	--	9.2E+2	1.1E+4	--	--
31	--	1.8E+4	4.1E+4	5.0E+3	1.6E+4
32	--	1.3E+3	2.9E+4	9.3E+3	--
33	--	8.4E+3	4.2E+3	--	--
35	--	2.9E+3	1.2E+4	--	--
36	--	--	2.2E+5	5.8E+3	--
38P	--	3.2E+3	5.0E+3	3.2E+3	--
38G	--	--	1.0E+4	--	--
41	--	9.3E+2	7.0E+4	8.7E+4	1.5E+4
43	--	3.5E+2	4.0E+3	1.6E+4	--
44	--	6.0E+2	8.0E+4	1.0E+5	--
45	--	--	2.1E+4	--	--

Table I-1 (continued). GAS STREAM (μg/m^3)

Compound	C_2-Thiophenes	Benzothiophene	Sodium	Potassium	Aluminum	TOC
Mol. Wt.	112	134	23	39	27	12
DMEG	2.6E+4	2.3E+4	5.3E+4	2.0E+3	5.2E+3	4.0E+4
Run No.						
6	2.3E+3	3.7E+3	--	--	--	--
16	--	2.7E+3	--	--	--	--
20	--	--	--	--	--	--
21	7.8E+4	--	--	--	--	--
23	9.4E+4	--	--	--	--	--
25	1.0E+3	--	--	--	--	--
26	3.0E+4	--	7.2E+1	7.8E+0	--	4.2E+3
31	4.0E+4	1.6E+4	--	--	--	--
32	1.6E+3	--	--	--	--	--
33	1.3E+4	--	--	--	--	--
35	9.3E+3	--	--	--	--	--
36	5.6E+2	--	--	--	--	--
38P	6.5E+3	--	--	--	--	--
38G	--	--	--	--	--	--
41	--	--	--	--	--	--
43	--	--	--	--	--	--
44	--	--	--	--	--	--
45	--	--	--	--	--	--

Table I-1 (continued). GAS STREAM ($\mu g/m^3$)

Compound	Carbon Monoxide	Carbon Dioxide	Lead	Ammonia	Hydrogen Cyanide	Arsenic
Mol. Wt.	28	44	207	17	17	75
DMEG	4.0E+4	9.0E+6	1.5E+2	1.8E+4	5.0E+3	2.0E+0
Run No.						
6	2.1E+8	4.1E+8	--	--	--	--
16	1.7E+8	3.0E+8	--	--	--	1.0E+0
20	2.6E+8	2.8E+8	--	--	--	--
21	1.9E+8	3.4E+8	--	--	--	--
23	1.4E+8	3.0E+8	--	--	--	--
25	1.7E+8	4.7E+8	--	2.3E+5	2.6E+4	--
26	3.0E+8	1.8E+8	--	--	--	--
31	5.8E+8	3.2E+8	--	--	--	--
32	3.3E+8	1.7E+8	--	8.4E+4	3.0E+4	--
33	3.4E+8	8.4E+8	--	--	--	--
35	1.9E+8	2.4E+8	--	--	--	--
36	2.6E+8	2.0E+8	--	--	--	--
38P	9.6E+6	8.7E+7	--	--	--	--
38G	1.0E+8	2.7E+8	--	--	--	--
41	1.9E+8	2.8E+8	--	--	--	--
43	2.7E+8	1.7E+8	--	--	--	--
44	8.0E+7	3.1E+8	--	--	--	--
45	2.8E+8	1.8E+8	--	--	--	--

Table I-1 (continued). GAS STREAM ($\mu g/m^3$)

Compound	Antimony	Sulfur Dioxide	Hydrogen Sulfide	Carbonyl Sulfide	Carbon Disulfide
Mol. Wt.	122	64	34	60	76
DMEG	5.0E+2	1.3E+4	1.5E+4	3.8E+3	3.0E+3
Run No.					
6	--	2.7E+4	1.6E+7	1.8E+5	1.1E+4
16	--	--	8.5E+6	8.8E+4	1.7E+4
20	--	--	7.5E+6	7.3E+4	1.5E+3
21	--	--	7.6E+6	4.0E+4	1.0E+4
23	--	--	5.3E+6	2.2E+4	4.0E+3
25	--	--	1.7E+7	9.8E+4	4.4E+4
26	--	--	9.6E+5	3.1E+4	--
31	--	--	2.5E+6	5.0E+4	3.4E+3
32	--	--	9.8E+5	1.8E+5	7.5E+4
33	--	--	8.8E+5	5.1E+4	1.5E+5
35	--	--	1.3E+5	6.8E+4	1.4E+5
36	--	--	--	1.0E+6	7.5E+4
38P	--	--	1.8E+5	1.4E+6	1.5E+5
38G	--	--	4.0E+4	4.2E+6	1.4E+5
41	--	--	--	7.1E+6	1.5E+5
43	--	--	--	6.4E+5	1.2E+5
44	--	--	--	6.0E+6	2.9E+5
45	--	--	--	1.2E+6	1.4E+5

Table I-1 (continued). GAS STREAM ($\mu g/m^3$)

Compound	Selenium	Bromine	Scandium	Titantium	Chromium	Manganese	Cobalt
Mol. Wt.	76	160	45	48	52	55	59
DMEG	2.0E+2	7.0E+3	5.3E+4	6.0E+3	1.0E+3	5.0E+3	5.0E+1
Run No.							
6							
16			1.8E+5				
20							
21							
23							
25							
26							
31							
32							
33							
35							
36							
38P	1.0E+5						
38G	2.3E+4						
41	2.0E+2						
43	3.0E+3						
44	1.3E+4						
45	1.4E+3						

Table I-1 (continued). GAS STREAM ($\mu g/m^3$)

Compound	Copper	Cadmium	Mercury	Hydrogen
Mol. Wt.	64	112	201	2
DMEG	2.0E+2	1.0E+1	5.1E+1	4.1E+5
Run No.				
6				5.0E+7
16				3.0E+7
20				2.8E+7
21				2.7E+7
23				2.0E+7
25				1.5E+7
26				1.2E+7
31				3.3E+7
32				1.7E+7
33				1.6E+7
35				1.1E+7
36				1.2E+7
38P				--
38G				6.6E+6
41				1.4E+7
43				1.1E+7
44				1.1E+7
45				1.4E+7

TABLE I-2. CONCENTRATION OF SPECIES IN AQUEOUS CONDENSATE
(micrograms per liter)

Compound	Phenol	Cresols	Xylenols	Trimethylphenol	1-Methylnaphthalene
Mol. Wt.	094	108	122	134	
DMEG	1.7E+4	5.0E+0	5.0E+0	5.0E+0	3.4E+6
Run No.					
6					
16	2.0E+5	3.4E+5	--	--	--
20	--	--	--	--	--
21	4.7E+4	1.1E+5	6.8E+4	1.8E+4	--
23	1.3E+5	1.6E+5	6.3E+4	--	--
25	4.9E+5	2.2E+5	1.8E+4	--	--
26					
31	5.9E+5	3.6E+5	3.7E+4	--	--
32	4.1E+6	7.2E+5	1.6E+5	--	--
33	3.3E+5	3.6E+5	1.3E+5	--	--
35	1.8E+6	1.1E+6	2.3E+5	--	--
36	1.0E+6	5.3E+5	1.3E+5	--	--
38P	2.9E+4	3.5E+4	2.6E+4	--	--
38G	7.7E+5	8.6E+5	3.4E+5	--	--
41	3.9E+5	3.5E+5	4.9E+4	--	--
43	2.7E+6	1.5E+6	3.1E+5	--	--
44	--	--	4.8E+2	--	--
45					

Table I-2 (continued). AQUEOUS CONDENSATE (μg/L)

Compound	2-Methylnaphthalene	Anthracene	Phenanthrene	Acenaphthylene	Chrysene
Mol. Wt.					
DMEG	3.4E+6	8.4E+5	2.4E+4	2.4E+4	3.3E+4
Run No.					
6					
16					
20					
21					
23					
25					
26					
31					
32					
33					
35					
36					
38P					
38G					
41					
43	2.2E+2	4.1E+1	9.6E+1	5.7E+1	1.6E+2
44					
45					

Table I-2 (continued). AQUEOUS CONDENSATE (μg/L)

Compound	Triphenylene	Fluorene	Fluoranthene	Benzo(a)pyrene	Benzo(e)pyrene
Mol. Wt.					
DMEG	3.9E+0	6.8E+5	1.4E+6	3.0E-1	4.6E+4
Run No.					
6					
16					
20					
21					
23					
25					
26					
31					
32					
33					
35					
36					
38P					
38G					
41					
43	0.5E+2	5.7E+1	2.8E+1	3.6E+1	2.1E+1
44					
45					

Table I-2 (continued). AQUEOUS CONDENSATE (μg/L)

Compound	Perylene	Benzo(k)fluoranthene	Benzo(b)fluoranthene	Lead	Nitrates
Mol. Wt.				207	078
DMEG	3.0E-1	2.4E+5	1.3E+4	2.5E+2	1.4E+5
Run No.					
6					
16	--	--	--	1.3E+3	--
20					
21	--	--	--	3.0E+1	1.0E+1
23	--	--	--	1.2E+1	--
25	--	--	--	6.9E+1	1.0E+1
26					
31					
32	--	--	--	1.4E+1	--
33	--	--	--	1.3E+1	--
35	--	--	--	2.1E+1	--
36	--	--	--	4.4E+1	--
38P					
38G					
41					
43	2.1E+1	1.7E+1	3.3E+1		
44					
45					

Table I-2 (continued). AQUEOUS CONDENSATE ($\mu g/L$)

Compound	Cyanide	Hydrogen Cyanide	Ammonia	Phosphorus	Arsenic	Sulfur	Thiocyanate
Mol. Wt.	026	027	017	031	075	032	058
DMEG	1.0E+3	1.0E+3	2.5E+3	1.5E+4	2.0E+0	2.0E+5	8.7E+3
Run No.							
6							
16	--	--	--	--	6.7E+1	--	--
20	3.5E+3	--	4.0E+6	1.0E+2	2.3E+2	5.7E+5	2.7E+5
21	3.5E+3	--	4.0E+6	1.0E+2	2.3E+2	5.7E+5	2.7E+5
23	--	--	--	--	1.0E+2	--	--
25	1.3E+4	--	7.9E+6	1.0E+2	--	8.4E+5	2.1E+5
26							
31	--	--	3.1E+6	--	--	--	--
32	--	5.1E+3	--	--	--	--	--
33							
35							
36	--	8.6E+3	5.3E+6	--	2.9E+1	--	--
38P							
38G	--	--	--	--	9.7E+2	--	--
41							
43							
44							
45							

Table I-2 (continued). AQUEOUS CONDENSATE (µg/L)

Compound	Antimony	Selenium	Chlorides	Bromine	Scandium	Titanium	Vanadium	Chromium
Mol. Wt.	122	079	035	080	045	048	051	052
DMEG	2.3E+2	2.2E+1	1.3E+6	1.3E+6	8.0E+5	9.0E+4	2.5E+3	8.0E-1
Run No.								
6								
16	1.5E+1	--	--	--	--	--	--	5.0E+2
20								
21	3.5E+0	--	2.2E+6	--	--	--	--	2.9E+2
23	9.6E+0	--	--	--	--	--	--	3.6E+2
25	--	--	1.1E+6	--	--	--	--	4.6E+2
26	4.0E+0	--	--	--	--	--	--	3.2E+3
31								
32	--	--	--	--	--	--	--	3.4E+2
33	--	--	--	--	--	--	--	2.6E+2
35								
36								
38P								
38G								
41								
43								
44								
45								

Table I-2 (continued). AQUEOUS CONDENSATE (μg/L)

Compound	Manganese	Iron	Cobalt	Nickel	Copper	Zinc	Cadmium	Mercury
Mol. Wt.	055	056	059	059	064	065	112	201
DMEG	2.5E+2	1.5E+3	7.5E+2	2.5E+2	5.0E+3	8.4E+4	5.0E+0	1.0E+0
Run No.								
6								
16	--	--	--	--	--	--	9.6E+1	--
20								
21	--	--	--	--	--	--	3.8E+0	--
23	--	--	--	--	--	--	1.3E-1	--
25	--	--	--	--	--	--	4.4E+0	--
26	--	--	--	--	--	--	8.5E+0	--
31								
32	--	--	--	--	--	--	3.4E-1	--
33	--	--	--	--	--	--	7.3E+0	--
35	--	--	--	--	--	--	1.5E+1	--
36	1.8E+2	--	--	--	--	--	1.3E-1	--
38P								
38G								
41								
43								
44								
45								

TABLE I-3. CONCENTRATION OF SPECIES IN GASIFIER TAR
(micrograms per gram of tar)

Compound	Aniline	Benzidine	Biphenyl	Phenol	Cresols	Xylenols	Trimethylphenol
Mol. Wt.	093	184	--	094	108	122	134
DMEG	6.0E+4	3.0E+3	3.0E+3	3.4E+3	1.0E+0	1.0E+0	1.0E+0
Run No.							
6							
16	--	3.1E+3	1.9E+3	2.2E+2	5.3E+2	--	--
20	1.5E+2	--	--	--	--	--	--
21	2.7E+2	5.0E+2	2.6E+3	2.9E+3	1.1E+4	2.7E+3	--
23	--	6.0E+2	2.2E+3	--	--	--	--
25	--	2.0E+2	2.9E+3	4.6E+3	1.4E+4	1.1E+4	2.5E+3
26	3.8E+1	--	--	4.3E+3	7.6E+3	2.3E+3	6.9E+2
31	7.6E+1	--	--	1.7E+3	1.1E+4	5.2E+3	7.9E+2
32	1.3E+1	--	--	3.5E+3	1.1E+4	8.9E+3	1.2E+3
33	7.2E+1	3.0E+2	2.1E+3	1.3E+4	2.9E+3	2.2E+4	2.7E+3
35	4.8E+1	2.0E-3	1.5E+3	1.1E+4	2.7E+4	1.7E+4	1.4E+3
36	--	3.0E+2	3.8E+3	5.6E+3	1.1E+4	8.4E+2	1.7E+3
38P	8.0E+1	--	--	7.5E+2	2.3E+3	1.4E+3	1.3E+3
38G	9.3E+1	--	--	2.9E+3	1.9E+4	1.1E+4	--
41	2.1E+1	4.0E+2	2.9E+3	1.2E+3	8.6E+3	4.8E+3	1.7E+3
43	3.8E+0	2.0E+2	2.1E+3	5.1E+3	1.6E+4	1.2E+5	2.4E+4
44	3.3E+0	--	--	5.3E+2	1.4E+3	2.0E+3	1.7E+2
45							

Table I-3 (continued). GASIFIER TAR (μg/g)

Compound	o-Isopropylphenol	Naphthalene	C_2-(alkyl)naphthalene	1-Methylnaphthalene
Mol. Wt.	134	128		
DMEG	1.0E+0	1.5E+4	6.8E+5	6.8E+5
Run No.				
6				
16	--	1.7E+3	2.8E+3	5.1E+3
20	--	2.3E+4	--	--
21	--	5.7E+4	1.1E+4	3.3E+3
23	--	--	7.4E+3	2.5E+3
25	2.5E+3	2.6E+4	1.6E+4	7.9E+3
26	--	1.2E+4	--	--
31	1.9E+3	6.5E+3	--	--
32	5.3E+2	1.1E+4	--	--
33	9.5E+2	7.4E+3	6.4E+3	5.2E+3
35	6.2E+5	1.6E+3	8.2E+3	4.9E+3
36	5.0E+2	2.2E+6	6.9E+6	7.1E+6
38P	1.3E+3	8.4E+1	--	--
38G	5.4E+3	1.5E+3	--	--
41	7.2E+2	8.5E+3	2.0E+3	3.4E+3
43	2.9E+3	3.6E+3	7.9E+3	4.9E+3
44	--	1.8E+4	--	--
45				

Table I-3 (continued). GASIFIER TAR (μg/g)

Compound	2-Methylnaphthalene	Acenaphthylene	Acenaphthene	Anthracene
Mol. Wt.	142			178
DMEG	6.8E+5	4.8E+3	4.8E+3	16.8E+4
Run No.				
6				
16	--	7.8E+5	2.7E+5	1.1E+6
20	4.8E+5	--	--	--
21	1.0E+4	1.2E+4	3.8E+3	--
23	--	1.1E+4	2.7E+3	--
25	4.3E+3	1.8E+4	4.1E+3	7.4E+3
26	1.0E+4	--	--	6.2E+3
31	2.2E+3	--	--	3.6E+3
32	6.1E+3	--	--	1.5E+4
33	6.3E+3	4.8E+4	2.2E+3	6.8E+3
35	3.8E+3	1.7E+3	1.5E+3	2.6E+3
36	4.3E+3	1.5E+4	3.9E+3	1.2E+4
38P	9.5E+2	--	--	1.1E+3
38G	3.8E+3	--	--	3.2E+3
41	6.4E+3	6.0E+3	4.2E+3	2.3E+4
43	4.5E+3	3.1E+3	1.8E+3	6.7E+3
44	5.2E+3	--	--	2.1E+4
45				

Table I-3 (continued). GASIFIER TAR (μg/g)

Compound	Phenanthrene	9-Methylanthracene	Benz(a)anthracene	Triphenylene
Mol. Wt.	178	190		
DMEG	4.8E+3	4.8E+3	13.4E+1	7.8E+0
Run No.				
6				
16	3.5E+3	--	1.4E+3	2.0E+3
20	--	1.8E+4	1.3E+3	--
21	2.3E+4	1.6E+4	4.7E+3	4.6E+3
23	--	--	2.8E+3	3.2E+3
25	2.3E+4	--	7.0E+3	6.2E+3
26	1.8E+4	3.1E+3	--	--
31	1.5E+4	1.9E+3	--	--
32	6.5E+3	2.0E+2	--	--
33	3.4E+3	1.2E+2	4.0E+2	6.0E+2
35	1.6E+3	1.9E+3	2.0E+2	3.0E+2
36	7.4E+3	1.7E+2	2.1E+3	2.5E+3
38P	1.5E+3	4.8E+3	--	--
38G	4.1E+3	9.8E+3	--	--
41	2.2E+4	4.3E+3	1.2E+3	4.1E+3
43	2.3E+6	7.6E+4	1.0E+5	1.0E+5
44	8.6E+6	1.7E+6	--	--
45				

Table I-3 (continued). GASIFIER TAR (μg/g)

Compound	Perylene	Fluorene	Fluoranthene	Benzo(g,h,i)perylene	Benzo(a)fluorene
Mol. Wt.	252	166	202		
DMEG	6.0E+0	13.6E+4	2.8E+5	13.0E+1	15.4E+4
Run No.					
6					
16	--	7.4E+1	6.2E+3	1.0E+2	1.8E+3
20	2.9E+3	5.2E+3	9.8E+3	--	--
21	--	8.0E+3	1.3E+4	1.8E+3	2.6E+3
23	--	--	--	1.1E+3	1.8E+3
25	3.7E+3	4.6E+2	1.3E+4	2.7E+3	4.1E+3
26	2.7E+4	7.3E+3	1.1E+4	--	--
31	1.2E+3	3.2E+3	8.4E+3	--	--
32	6.7E+3	4.2E+3	1.3E+4	--	--
33	1.1E+3	4.7E+3	2.7E+3	6.0E+1	1.2E+3
35	2.4E+2	1.7E+3	4.1E+5	--	1.1E+3
36	8.3E+5	4.8E+3	7.6E+3	2.0E+2	2.6E+3
38P	--	5.9E+2	5.0E+2	--	--
38G	--	1.5E+3	2.0E+3	--	--
41	--	7.5E+3	3.4E+4	2.0E+2	9.0E+2
43	8.6E+1	4.0E+3	1.5E+3	2.0E+1	4.0E+2
44	1.5E+3	5.1E+3	1.6E+4	--	--
45					

Table I-3 (continued). GASIFIER TAR (μg/g)

Compound	Chrysene	Pyrene	Dibenzo(a,h)anthracene	Benzo(a)pyrene	Benzo(e)pyrene
Mol. Wt.	228	202			
DMEG	6.6E+3	6.8E+3	2.8E+0	6.0E+0	9.2E+3
Run No.					
6					
16	--	1.8E+3	2.0E+2	6.0E+2	4.0E+2
20	5.9E+3	7.4E+3	--	--	--
21	8.0E+3	9.0E+3	2.8E+3	3.5E+3	2.1E+3
23	--	--	1.6E+3	2.0E+3	1.2E+3
25	8.6E+3	1.1E+4	3.4E+3	2.7E+3	1.9E+3
26	7.3E+3	1.0E+4	--	--	--
31	5.2E+3	8.4E+3	--	--	--
32	8.7E+3	1.2E+4	--	--	--
33	1.7E+3	2.1E+3	1.0E+2	3.0E+5	3.0E+2
35	6.9E+2	1.2E+3	--	5.0E+1	3.0E+1
36	2.6E+3	4.8E+3	3.0E+2	1.1E+3	6.0E+2
38P	--	3.4E+2	--	--	--
38G	2.5E+3	1.8E+3	--	--	--
41	--	2.4E+4	4.0E+2	1.7E+3	1.4E+3
43	5.8E+3	1.3E+3	2.0E+1	2.0E+1	1.0E+1
44	1.8E+4	1.7E+4	--	--	--
45					

Table I-3 (continued). GASIFIER TAR (μg/g)

Compound	Benzo(b)fluorene	Benzo(k)fluoranthene	Benzo(b)fluoranthene
Mol. Wt.			
DMEG	15.4E+4	9.6E+4	2.6E+3
Run No.			
6			
16	9.0E+2	7.0E+2	1.0E+3
20			
21	1.7E+3	1.6E+3	3.1E+3
23	9.0E+2	9.0E+2	1.8E+3
25	2.4E+3	1.2E+3	2.5E+3
26			
31			
32			
33	8.0E+2	3.0E+2	4.0E+2
35	9.0E+2	4.0E+1	6.0E+1
36	1.7E+3	1.1E+3	1.4E+3
38P			
38G			
41	6.0E+2	1.0E+3	1.2E+3
43	3.0E+2	2.0E+1	3.0E+1
44			
45			

Table I-3 (continued).. GASIFIER TAR (μg/g)

Compound	Indeno(1,2,3-cd)pyrene	Quinoline	Acridine	Indole	Carbazole
Mol. Wt.					
DMEG	4.8E+3	4.8E+3	2.8E+5	3.2E+4	7.0E+4
Run No.					
6					
16	1.0E+2	--	--	--	8.0E+2
20	--	2.2E+3	1.7E+3	3.7E+1	--
21	1.4E+3	3.1E+3	1.7E+3	5.8E+1	1.2E+3
23	8.0E+2	--	--	--	1.2E+3
25	1.7E+3	2.5E+3	1.5E+3	--	2.6E+3
26	--	2.9E+3	7.7E+2	3.8E+4	--
31	--	2.2E+3	1.4E+3	3.8E+1	--
32	--	9.7E+2	3.4E+2	6.7E+0	--
33	5.0E+1	8.3E+2	2.0E+2	1.2E+1	6.0E+2
35	--	1.2E+2	3.4E+1	2.4E+1	5.0E+2
36	1.0E+2	1.4E+3	1.0E+3	--	5.0E+2
38P	--	8.0E+1	8.0E+2	--	--
38G	--	5.3E+2	1.2E+2	2.3E+1	--
41	3.0E+2	1.1E+3	4.7E+2	8.0E+0	1.7E+3
43	2.0E+1	2.5E+2	2.5E+1	2.4E+4	9.0E+2
44	--	7.6E+2	7.0E+2	6.7E+0	--
45					

Table I-3 (continued). GASIFIER TAR (μg/g)

Compound	Dibenzofuran	Benzothiophene	Lead	Arsenic	Antimony	Sulfur
Mol. Wt.	168		207	075	122	032
DMEG	10.4E+5	7.0E+4	5.0E+1	4.0E+0	14.6E+1	4.0E+4
Run No.						
6	--	--	8.5E-1	1.3E+0	--	1.9E+4
16	8.9E+3	6.6E+3	--	--	--	1.6E+4
20	4.6E+3	--	1.1E+0	4.2E+0	--	--
21	7.4E+3	5.3E+3	3.1E-1	1.9E+1	--	1.8E+4
23	--	3.6E+3	4.9E-1	--	--	--
25	5.2E+3	1.7E+3	--	--	7.0E-2	--
26	5.4E+3	--	--	--	--	7.1E+3
31	2.0E+3	--	3.3E+1	--	2.3E-1	--
32	3.4E+3	--	1.1E+1	--	1.2E-1	--
33	3.4E+3	8.0E+2	7.3E-1	--	9.8E-2	--
35	1.4E+3	4.0E+2	--	--	--	--
36	3.7E+3	3.3E+3	2.5E+0	8.0E-1	5.0E-1	--
38P	--	7.5E+2	--	--	--	--
38G	--	2.3E+3	--	--	5.7E-1	--
41	8.1E+3	8.7E+3	--	--	--	--
43	9.0E+2	4.7E+3	7.0E+2	--	--	--
44	9.2E+3	--	--	--	--	--
45						

Table I-3 (continued). GASIFIER TAR (ug/g)

Compound	Selenium	Bromine	Scandium	Titanium	Vanadium	Chromium	Manganese
Mol. Wt.	079	080	045	048	051	052	055
DMEG	4.4E+0	2.6E+5	16.0E+4	18.0E+3	5.0E+2	16.0E+0	5.0E+1
Run No.							
6							
16							
20							
21							
23							
25	--	--	--	--	--	1.1E+1	--
26							
31	--	--	--	--	--	4.1E+1	--
32	--	--	--	--	--	5.2E+0	--
33	--	--	--	--	--	9.4E+1	--
35							
36	--	--	--	--	--	2.0E+2	--
38P							
38G							
41							
43							
44							
45							

Table I-3 (continued). GASIFIER TAR ($\mu g/g$)

Compound	Iron	Cobalt	Nickel	Copper	Zinc	Cadmium	Mercury
Mol. Wt.	056	059	059	064	065	112	201
DMEG	3.0E+2	15.0+1	5.0E+1	6.0E+2	16.8E+3	10.0E+0	2.0E+0
Run No.							
6							
16							
20	--	--	--	--	--	3.5E-2	--
21	--	--	--	--	--	2.7E-2	--
23							
25	--	--	--	--	--	1.3E-1	--
26							
31	--	--	--	--	--	6.7E-2	--
32							
33	--	--	--	--	--	1.7E-2	--
35	--	--	--	--	--	5.0E-2	--
36							
38P							
38G							
41							
43							
44							
45							

TABLE I-4. CONCENTRATION OF SPECIES IN SOLID RESIDUE
(micrograms per gram of residue)

Compound	Antimony	Selenium	Bromine	Chloride	Scandium	Titanium
Mol. Wt.	122	079	080	057	045	051
DMEG	1.5E+3	1.7E+0	2.6E+5	2.6E+5	1.6E+6	1.8E+5
Run No.						
6	--	1.0E+1	--	--	--	--
16	--	3.0E+0	--	--	--	--
20	--	2.6E+0	--	--	--	--
21	--	1.4E+0	--	--	--	--
23	--	1.7E+0	--	--	--	--
25	--	--	--	--	--	--
26	--	9.1E-2	--	--	--	--
31	--	--	--	--	--	--
32	--	--	--	--	--	--
33	--	--	--	--	--	--
35	--	5.8E+0	--	3.0E-1	--	--
36	--	--	--	7.9E-1	--	--
38P						
38G						
41	--	9.9E+0	--	1.0E-1	--	--
43	--	8.6E+0	--	--	--	--
44						
45	--	8.8E+0	--	1.2E+0	--	--

Table I-4 (continued). SOLID RESIDUE (μg/g)

Compound	Vanadium	Sodium	Rubidium	Beryllium	Magnesium	Aluminum	Lead	Arsenic
Mol. Wt.	051	023	085	009	024	027	207	075
DMEG	5.0E+2	1.6E+7	3.6E+5	6.0E+0	1.8E+5	1.6E+4	5.0E+1	5.0E+1
Run No.								
6	--	--	--	--	--	--	--	--
16	--	--	--	--	--	--	--	1.3E+1
20	--	--	--	--	--	--	--	2.4E+1
21	6.5E+0	--	--	--	--	--	9.4E+0	1.2E+1
23	4.5E+0	--	--	--	--	--	4.9E+0	9.1E+0
25	4.9E+0	--	--	--	--	--	5.8E+0	--
26	4.6E+0	--	--	--	--	--	--	--
31								
32								
33								
35	3.4E+0	--	--	--	--	--	2.3E+0	--
36	3.6E+0	--	--	--	--	--	1.4E+0	4.1E+1
38P								
38G	--	--	--	--	--	--	--	1.2E+1
41	--	--	--	--	--	--	--	7.2E+0
43	--	--	--	--	--	--	3.0E-1	3.1E+1
44	--	--	--	--	--	--	--	2.2E+1
45	--	--	--	--	--	--	6.3E-1	--

Table I-4 (continued). SOLID RESIDUE (μg/g)

Compound	Mercury	Cerium	Lanthanum	Samarium	Thorium
Mol. Wt.	201	140	139	150	169
DMEG	2.0E+0	1.1E+5	3.4E+5	1.6E+5	1.3E+2
Run No.					
6					
16	3.1E-3	--	--	--	--
20	--	--	--		
21	4.7E-3	--	--	--	--
23	3.8E-3	--	--	--	--
25	8.9E-3	--	--	--	--
26	9.1E-3	--	--	--	--
31					
32					
33					
35	1.0E-2	--	--	--	--
36					
38P					
38G					
41					
43					
44					
45	1.1E-2	--	--	--	--

Table I-4 (continued). SOLID RESIDUE (μg/g)

Compound	Chromium	Manganese	Iron	Cobalt	Nickel	Copper	Zinc	Cadmium
Mol. Wt.	052	055	056	059	059	064	065	112
DMEG	5.0E+1	5.0E+1	3.0E+2	1.5E+2	4.5E+1	1.0E+3	5.0E+3	1.0E+1
Run No.								
6								
16								
20								
21	2.5E+2	--	--	--	--	--	--	8.8E-1
23	2.0E+2	--	--	--	--	--	--	7.1E-1
25	1.2E+2	--	--	--	--	--	--	2.7E-2
26	6.7E+2	--	--	--	--	--	--	7.3E+0
31								
32								
33								
35	1.9E+2	--	--	--	--	--	--	2.2E-1
36	2.5E+3	--	--	--	--	--	--	5.0E-1
38P								
38G								
41	1.8E+0	--	--	--	--	--	--	--
43	5.8E-1	--	--	--	--	--	--	5.8E-1
44								
45	2.0E+2	--	--	--	--	--	--	1.1E-2